

AN ABSTRACT OF THE THESIS OF

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the Claisen Rearrangement of Cis- and Trans- $\alpha$ ,  $\gamma$ -  
Dimethylallyl Phenyl Ethers

Abstract approved   
(Major professor)

Re-investigation of the Claisen rearrangement of cis- and trans-2-phenoxy-pent-3-ene ( $\alpha$ ,  $\gamma$ -dimethylallyl phenyl ether) in normal octane, has in essence, confirmed the previous results that the trans-phenol is the predominant product from both ethers. Moreover, both produce a small amount of cis-2-(o-hydroxyphenyl)-pent-3-ene but the amount formed from the trans-ether is greater than that from the cis-ether. A quantitative determination of the cis-product was not possible by standard infrared analysis.

It was shown that the two isomers undergo

rearrangement without prior cis to trans isomerization of the ethers. Analysis of ether recovered during the course of the rearrangement of the cis ether showed no cis- to trans-isomerization. Likewise, rearrangement in the presence of initially added excess phenolic product produced no effect on the recovered ether.

The rates of rearrangement of both ethers follow first-order kinetics. The overall rate constants were determined at 165°C;  $k_{\text{trans}} = 1.4 \times 10^{-5} \text{ sec}^{-1}$ ,  $k_{\text{cis}} = 0.95 \times 10^{-5} \text{ sec}^{-1}$ . Determination of the individual rates of formation of cis- and trans-phenol for each ether was not possible.

Slow conversion of the cis-phenol to the trans-phenol occurred but the rate of isomerization was slower than the rates of rearrangement by a factor of at least 10.

SOME STUDIES RELATING TO THE  
STEREOCHEMISTRY OF THE CLAISEN  
REARRANGEMENT OF CIS- AND TRANS-  
α, γ-DIMETHYLALLYL PHENYL ETHERS

by

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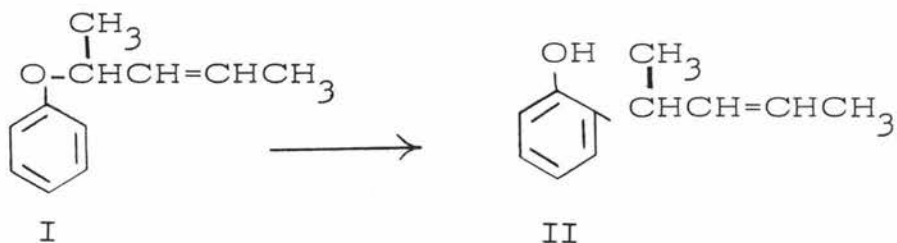
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# SOME STUDIES RELATING TO THE STEREOCHEMISTRY OF THE CLAISEN REARRANGEMENT OF CIS- AND TRANS- α,γ-DIMETHYLALLYL PHENYL ETHERS

## INTRODUCTION

The mechanistic postulations set forth by Claisen in 1925 on the well known rearrangement bearing his name (5 , p. 278) have been verified experimentally. The rearrangement proceeds through a cyclic transition state (5 , p. 278; 35 , p. 5866; 31 , p. 2217), is kinetically first order and unimolecular (14 , p. 3277; 22 , p. 3085), intramolecular (19 , p. 107; 36 , p. 1879), and involves inversion of the allyl side chain (35, p. 5867).

However, until recently, no attempt had been made to study the geometrical relationships amongst the rearranging atoms, except to show the inversion of the allyl moiety. Alexander and Kluiber (1 , p. 4306) found that the rearrangement



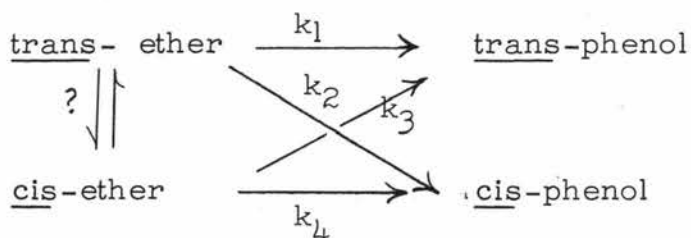
of optically active  $\alpha, \gamma$ -dimethylallyl phenyl ether (I) gave optically active 2-( $\alpha, \gamma$ -dimethylallyl)-phenol (II). Although the configuration of the starting material and final product was not clearly established, it can be seen that Hart's proposal that the reaction proceeds with retention of configuration (16, p. 4304) is inconsistent with the reasonable assumption that the transition state exists in a modified cyclohexane chair conformation.

The configuration of the new asymmetric center formed during the rearrangement can be directly correlated to the configuration of the original asymmetric center by studying the relation between the double bond configuration of the starting material and the product. The simplest case, the cis- and trans- $\alpha, \gamma$ -dimethylallyl phenyl ethers was studied by Marvell and Stephenson (29, p. 676). They observed predominantly trans product from both the cis and trans ether. In both cases, a small but significant amount of cis product was formed. However, the amount of cis product arising from the trans ether was greater than that from the cis ether. This result was confirmed by Burgstahler's study on trans- $\alpha, \gamma$ -dimethylallyl phenyl ether and trans- $\alpha, \gamma$ -dimethylallyl vinyl ether (4, p. 4681). However, Marvell and Stephenson's results are somewhat inconclusive since they observed that the cis- ether was



converted to the trans- ether during the reaction (29, p. 676).

The rates of rearrangement of the cis- and trans- $\alpha$ , $\gamma$ -dimethylallyl phenyl ether have not been determined. It is important to determine whether the two isomers rearrange independently of one another, and at the same time it would be interesting to establish the rate constants;  $k_{trans}$ ,  $k_{cis}$ ,  $k_1$ ,  $k_2$ ,  $k_3$  and  $k_4$  from the following kinetic scheme, where  $k_{trans} = k_1 + k_2$ , and  $k_{cis} = k_3 + k_4$ .



The main objectives of this re-investigation of the cis- and trans- $\alpha$ , $\gamma$ -dimethylallyl phenyl ether are; (1) to synthesize the pure cis- and trans-2( $\alpha$ , $\gamma$ -dimethylallyl) phenol by an independent route, to be used as standards for comparison with the rearrangement products; (2) to determine quantitatively the amount of cis and trans phenolic products from the cis and trans ethers; (3) to determine the rates of rearrangement of both isomers at 165°C, at which temperature only the normal rearrangement products result (28, p. 1109) and; (4) to study further the cis to trans interconversion of the starting ethers

as observed by Marvell and Stephenson (29, p. 676).

## HISTORICAL

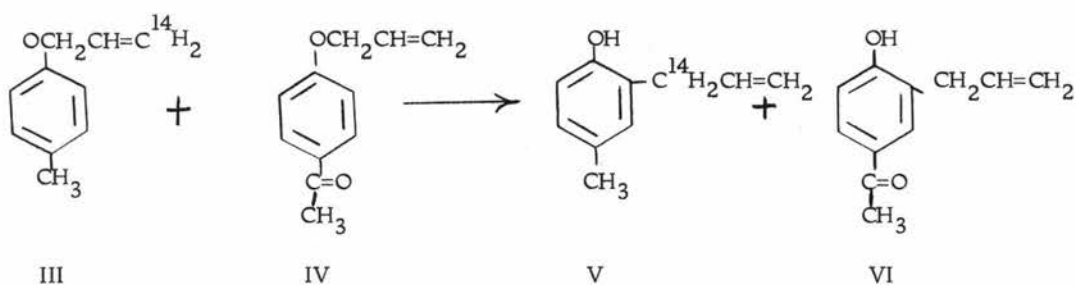
Organic reaction mechanisms may be classed under three main categories; ionic, radical and the so-called four-center or "no-mechanism" type. Reactions of the "no-mechanism" type are characterized by their susceptibility to thermal induction, and inertness to free radical initiators or inhibitors. They are intramolecular and involve a cyclic transition state, are insensitive to acidic or basic catalysis, are insensitive to solvent changes and show first-order kinetics. These reactions may be best illustrated by the Claisen and Cope (9 , p. 441) rearrangements, of which the Claisen rearrangement has been the most extensively studied (39, p. 1).

The Claisen rearrangement is a reaction in which allyl ethers of enols and phenols form C-allyl derivatives when heated. In the rearrangement of allyl phenyl ethers, the allyl group migrates exclusively to the ortho position if both are free. If the ortho positions are occupied, the allyl group migrates to the para position. However, when both ortho and para positions are blocked, complex side reactions occur, but the allyl group never migrates to the meta position (20, p. 1686; 6 , p. 81).

Since its discovery in 1912, elucidation of the nature of the rearrangement process has been accomplished primarily by kinetic measurements, demonstrations of intramolecularity, studies on the phenomenon of inversion and more recently by the stereochemical approach.

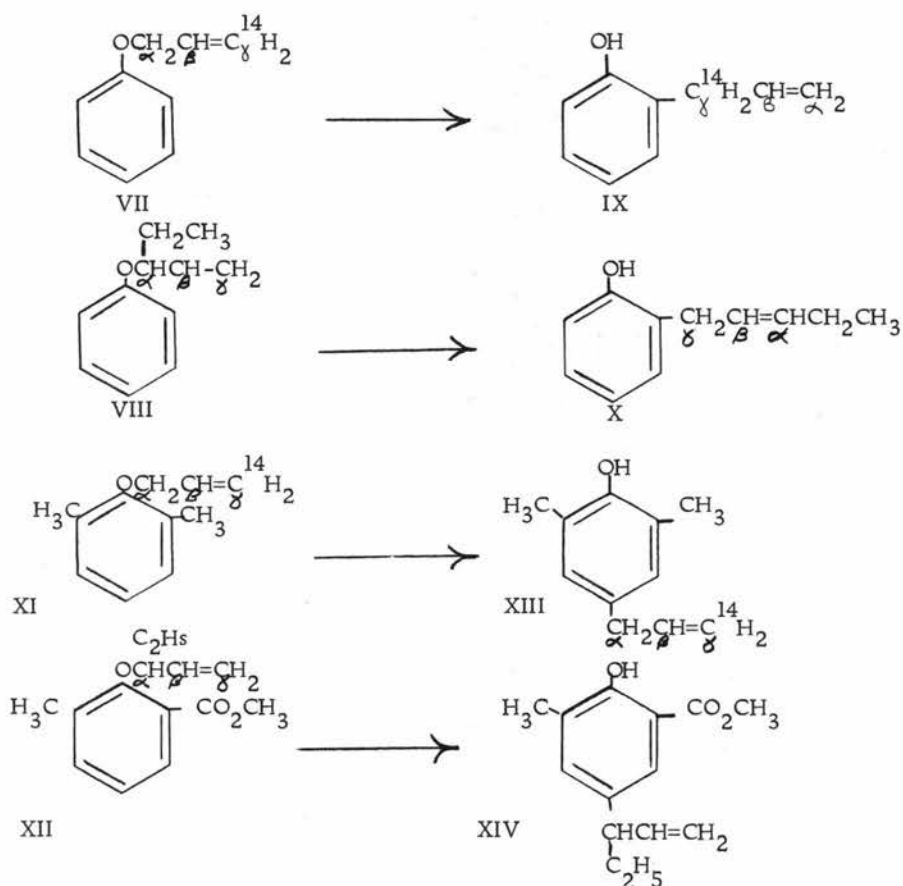
Kinetically, the ortho and para rearrangements have been shown to be strictly unimolecular. In recent studies on the ortho rearrangement by Goering and Jacobson (14, p. 3277) and later White and Slater (42, p. 2908), twenty-two different allyl phenyl ethers were subjected to Claisen conditions. All cases showed first-order kinetics during the rearrangement.

Attempts to detect fragments, ionic or radical, as intermediates during the course of rearrangement give negative results. The intramolecular character is well demonstrated by the lack of cross-products when a mixture of two differently



substituted ethers is allowed to rearrange. Thus, a mixture of allyl p-tolyl ether labeled with  $C^{14}$  (III) and allyl p-acetylphenyl ether (IV) rearranged to give only intramolecular products (V) and (VI) (36, p. 1879).

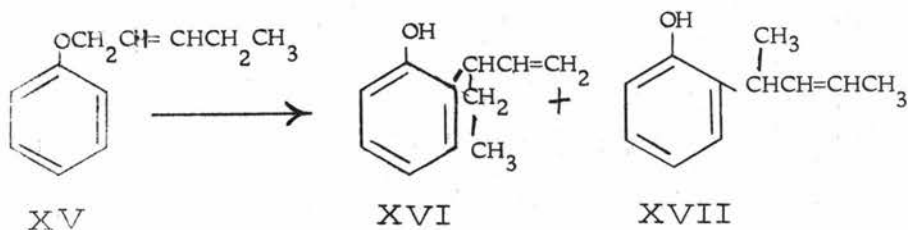
The question of inversion of the migrating allyl group is probably the most extensively studied aspect of the process. By appropriately labeling the  $\alpha$  or  $\gamma$ -carbon of the migrating



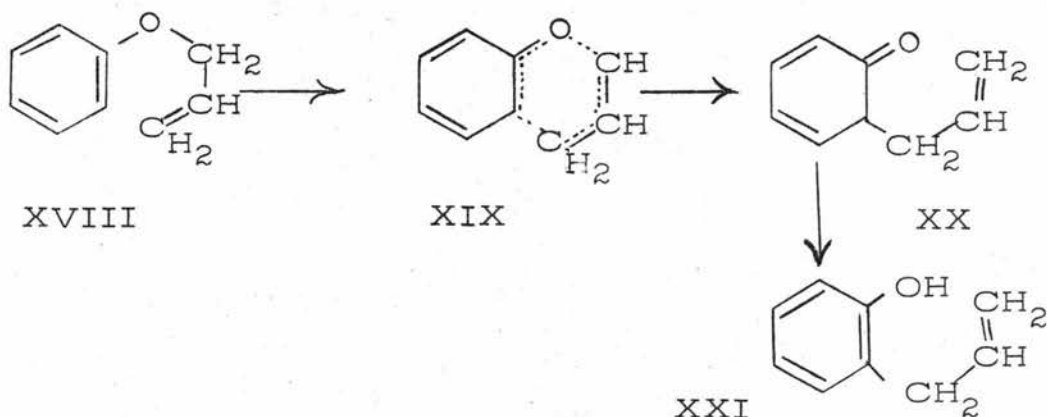
allyl group with  $C^{14}$  or alkyl substituents, it has been shown that inversion occurred in the ortho rearrangement, i.e., the  $\gamma$ -carbon of the allyl group becomes attached to the ring. However, this inversion does not occur on migration to the para position. For example, the ortho rearrangement of (VII) (35, p. 5867), and (VIII) (24, p. 1388), gave (IX) and (X), whereas the para rearrangement of (XI) (37, p. 489), and (XII) (33, p. 2531), gave (XIII) and XIV).

In general, the  $\gamma$ -carbon of the allyl group becomes attached to the ortho position of the aromatic ring. This applies to allyl phenyl ethers with alkyl substitution on the  $\alpha$ -carbon (24, p. 1388; 25, p. 3043; 26, p. 3047). However, alkyl groups on the  $\gamma$ -carbon lead to abnormal products in which the  $\beta$ -carbon becomes attached to the ortho position (25, p. 3043; 28, p. 1110; 15, p. 1943). Thus, it was shown by Hurd and Pollack (21, p. 550), and Lauer and Ungnade (26, p. 3047) that the rearrangement of  $\gamma$ -ethylallyl phenyl ether (XV) gave both the normal (XVI) and the abnormal (XVII) products.

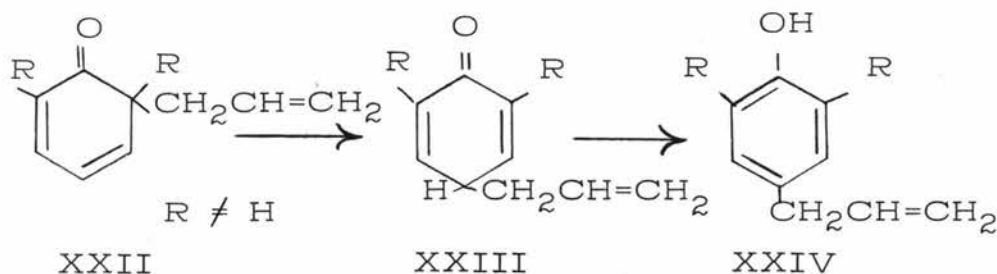
Aside from the phenomenon of the abnormal rearrangement just discussed, the observations of the intramolecularity, first-order kinetics and inversion of the migrating allyl group



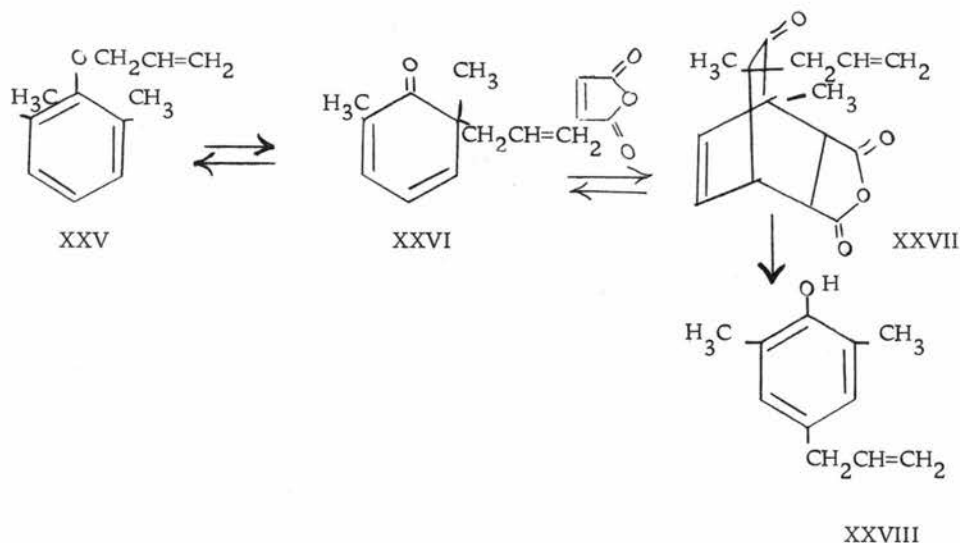
strongly suggests a cyclic mechanism. This mechanism, commonly referred to as the Hurd-Pollack mechanism (21, p. 550), proposes a cyclic, concerted process involving a quasi six-membered ring. The mechanism, now modified and extended to include both the ortho and para Claisen rearrangements, may be best illustrated by the following sequence with allyl phenyl ether (XVIII). In the ortho rearrangement, initial breakage of the old C-O bond occurs simultaneously with the formation of a new C-C bond, (XIX). The dienone (XX) is formed which enolizes rapidly to the product.



If both ortho positions are blocked, the dienone intermediate (XXII) cannot enolize but must rearrange once more.



The existence of the dienone intermediate has been verified by trapping it as a Diels-Alder adduct. This was first demonstrated by Conroy and Firestone in 1953 (7 , p. 2531). By rearranging allyl 2,6-dimethyl phenyl ether (XXV) in the presence of maleic anhydride, the adduct was obtained in low yield, and on heating, produced the same product as the para rearrangement (8 , p. 2290).

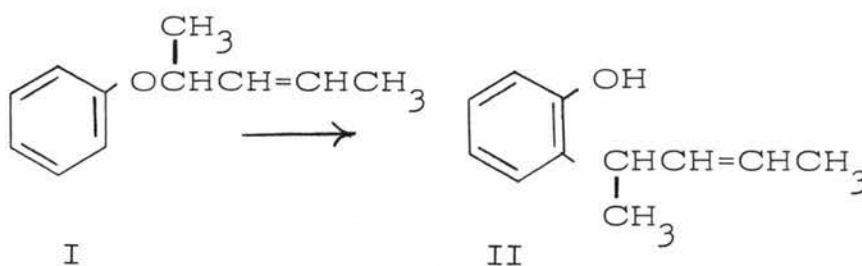




Moreover, the dienone (XXVI) was synthesized by Curtin and Crawford (10 , p. 3156) and shown to isomerize on heating to a mixture of phenol (XXVIII) and the allyl ether (XXV).

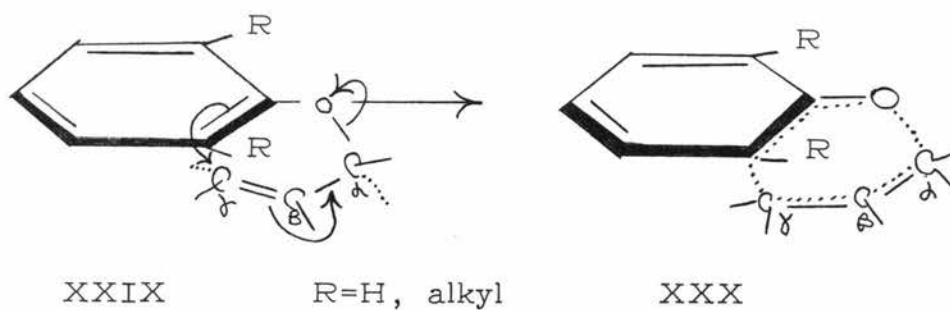
All the evidence cited thus far, provides conclusive information about the nature of the ortho and para rearrangement. However, the accumulated data only points out the gross features of the transition state. The subtle but intriguing nature of this transition state, i.e., the geometrical relationships between the rearranging atoms, has not been touched upon until recently.

The first example dealing with stereochemistry of the Claisen rearrangement was reported by Alexander and Kluiber (2 , p. 4304). It was shown that optically active  $\alpha,\gamma$ -dimethylallyl phenyl ether (I) rearranged to an optically active phenol (II).

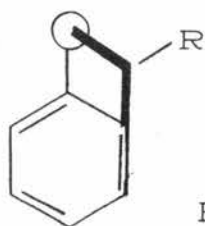


Hart suggested that the rearrangement occurred with retention of configuration (16, p. 4033). If a modified cyclohexane chair conformation is assumed as the most reasonable transition state, Hart's suggestion can be shown to be inconsistent with the results from conformational analysis.

In the para Claisen rearrangement, Rhoads et al. (34, p. 3456) suggested that in the transition state, the allyl group lies in a plane below and almost parallel with the ring. The  $\gamma$ -carbon of the allylic side chain is then positioned directly below the ortho-carbon of the aromatic nucleus. This is shown for the formation of the transition state (XXX) in the general case (XXIX). Thus it can be seen that there is a definite relationship between the change in geometry about the double bond and the change in configuration at the asymmetric center.

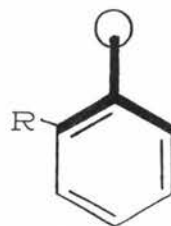


There are two extreme conformations possible for the transition state (XXX), both involving different orientations of the allyl group with respect to the aromatic ring. However, in either conformation, the allyl group is maintained nearly parallel to the plane of the ring. The  $\alpha$ -carbon of the allyl group is oriented over the ether oxygen and the  $\gamma$ -carbon directly over the *ortho*-position. The conformational differences lie in the position adopted by the  $\beta$ -carbon. It may be projected away from the rest of the molecule to form a quasi-chair conformation (XXXI) or lie directly superimposed over carbon-1 of the ring forming a quasi-boat conformation (XXXII).



R=H, alkyl

XXXI

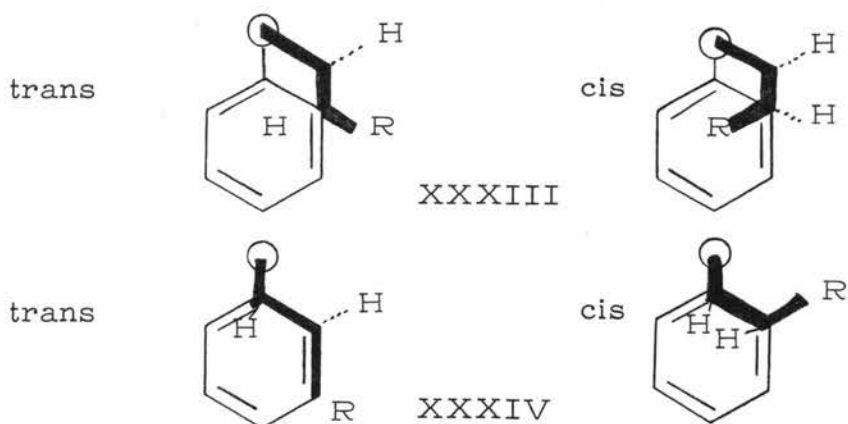


XXXII

The distinction between the two conformations was made by comparing the rates of rearrangement of a series of ethers having different  $\beta$ -alkyl substituents on the allyl side chain. If conformation (XXXII) were the preferred one, increasing the bulk of the substituent would increase the steric interaction

between  $\underline{R}$  and the aromatic nucleus, thereby slowing the rate. On the other hand, if conformation (XXXI) were favored, the rates should show no change with change in size of the alkyl group. The rate data of White and Norcross (41, p. 3265) support the conformation (XXXI) for the transition state.

Further insight into the stereochemistry may be gained by consideration of the double bond geometry of the  $\chi$ -alkyl-allyl phenyl ethers. Here again, distinction between the quasi-chair, and the quasi-boat conformation was made by rate studies. For a given cis and trans isomeric pair of ethers, there are four conformations; the quasi-chair forms (XXXIII), and the quasi-boat forms (XXXIV).



Because of steric interactions involved, it is clear that if the trans isomer rearranged faster than the cis, there would be strong evidence for the quasi-chair conformation. Conversely, the quasi-boat conformation would predict faster rates for the cis isomer. In recent studies by Huestis and Andrews (18, p. 1963) on the cis- and trans- isomers of  $\chi$ -methylallyl phenyl,  $\chi$ -phenylallyl phenyl and  $\chi$ -methylallyl 2,6-dimethyl phenyl ethers and the studies by White and Norcross (40, p. 1968) on the cis- and trans- $\chi$ -methylallyl p-methoxyphenyl, and  $\chi$ -phenylallyl p-methoxyphenyl ethers, the cis isomer does indeed rearrange more slowly than the trans. However, the rate difference is small and attempts to attribute this difference to conformational differences are questionable.

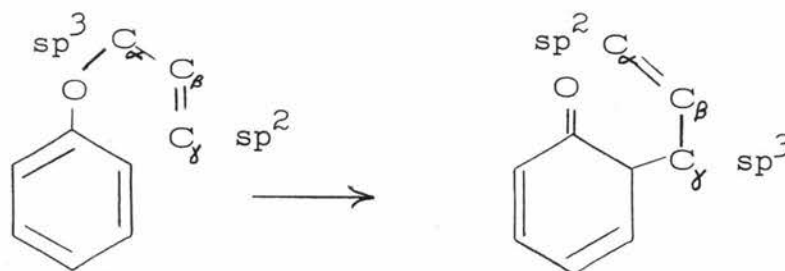
In addition to information provided by the cis and trans- $\chi$ -alkylallyl phenyl ethers, the stereochemistry of the rearrangement process can be studied in the cis and trans- $\alpha$ ,  $\chi$ -disubstituted allyl phenyl ethers. This particular system is advantageous in that the configuration of the new asymmetric center can be correlated directly to the configuration of the original asymmetric center by determination of the double bond geometry in the starting ether and the phenolic products. Marvell and Stephenson (29, p. 676) have shown the trans

phenol to be the predominant product in the cis and trans- $\alpha, \gamma$ -dimethylallyl phenyl ether system. Furthermore, by conformational analysis, the cis product is predicted from both isomers but the amount from the trans ether should exceed that from the cis ether. Again, experimental evidence supports this prediction (29, p. 676). Finally, the rates of rearrangement of the cis and trans isomeric pairs should parallel the rates of the cis and trans- $\gamma$ -substituted allyl phenyl ethers, i.e., the trans isomer rearranges faster than the cis isomer. At the present, no rate data have been reported for the cis and trans- $\alpha, \gamma$ -dimethylallyl phenyl ethers.

## DISCUSSION

The cyclic nature of the transition state of the Claisen rearrangement has been clearly established from previous studies. However, little attention was given to the more subtle problem of the transition state structure until recently. White has, on the basis of kinetic studies, provided data with some bearing on this problem, although the more direct application of stereochemical tools has been lacking.

Although the normal procedure is to find a model to fit experimental data, the reverse process will be used in part here. Since the cyclic transition state is established by experimental data, a model will be assumed for it and the predictions that can be made from this model will be considered. The choice of models will be restricted by the changes in bond hybridization required by the rearrangement process. Thus, for example, the alpha carbon of the allyl entity



changes from  $sp^3$  to  $sp^2$  hybridization while the gamma carbon undergoes the reverse change.

For maximum delocalization in the transition state, the allyl grouping must take on a planar geometry such that the p-orbitals on all three carbons are perpendicular to the plane. Therefore, the model chosen must approach this ideal condition. Since the three remaining atoms of the rearrangement make up a second allyl system, the model should be treated as a pair of planar three-atom groups. There are three possible arrangements which can be considered as shown.



In (A), the two planes are parallel to one another and the middle atom of each allyl system has maximum separation from the other (pseudo chair form). Arrangement (B) has the two planes inclined towards each other and the three pairs of atoms lie opposite one another (pseudo boat form). The third possibility (C) is that in which the two planes are coincident and can be ruled out for steric reasons. Both (A) and (B)



will provide the same conclusions but model (A) will be chosen because for comparison purposes, more useful data is available.

Two parameters are to be considered in the rearrangement of the  $\alpha, \gamma$ -dimethylallyl phenyl ether, the double bond configuration and the asymmetric  $\alpha$ -carbon. The configuration of the asymmetric center may be arbitrarily set since the enantiomeric model must give identical though mirror image results.

Consider first the trans-ether case. Here two possible routes are available to the ether as shown in Figure 1. If the rearrangement occurs via transition state (I), both methyl groups are situated in equatorial-like positions, and the new asymmetric center has an inverted configuration. However, the new double bond has the trans configuration. On the other hand, in the rearrangement via (II), the  $\gamma$ -methyl group is maintained in the equatorial position as required by the initial trans double bond, but the  $\alpha$ -methyl group occupies an axial-like position. If this system is assumed to be analogous to the cyclohexane ring system, an equatorial methyl is more stable than an axial one. Since both routes have the same ground state, the relative rates of rearrangement via (I) or (II) are determined only by the relative stabilities of the two transition

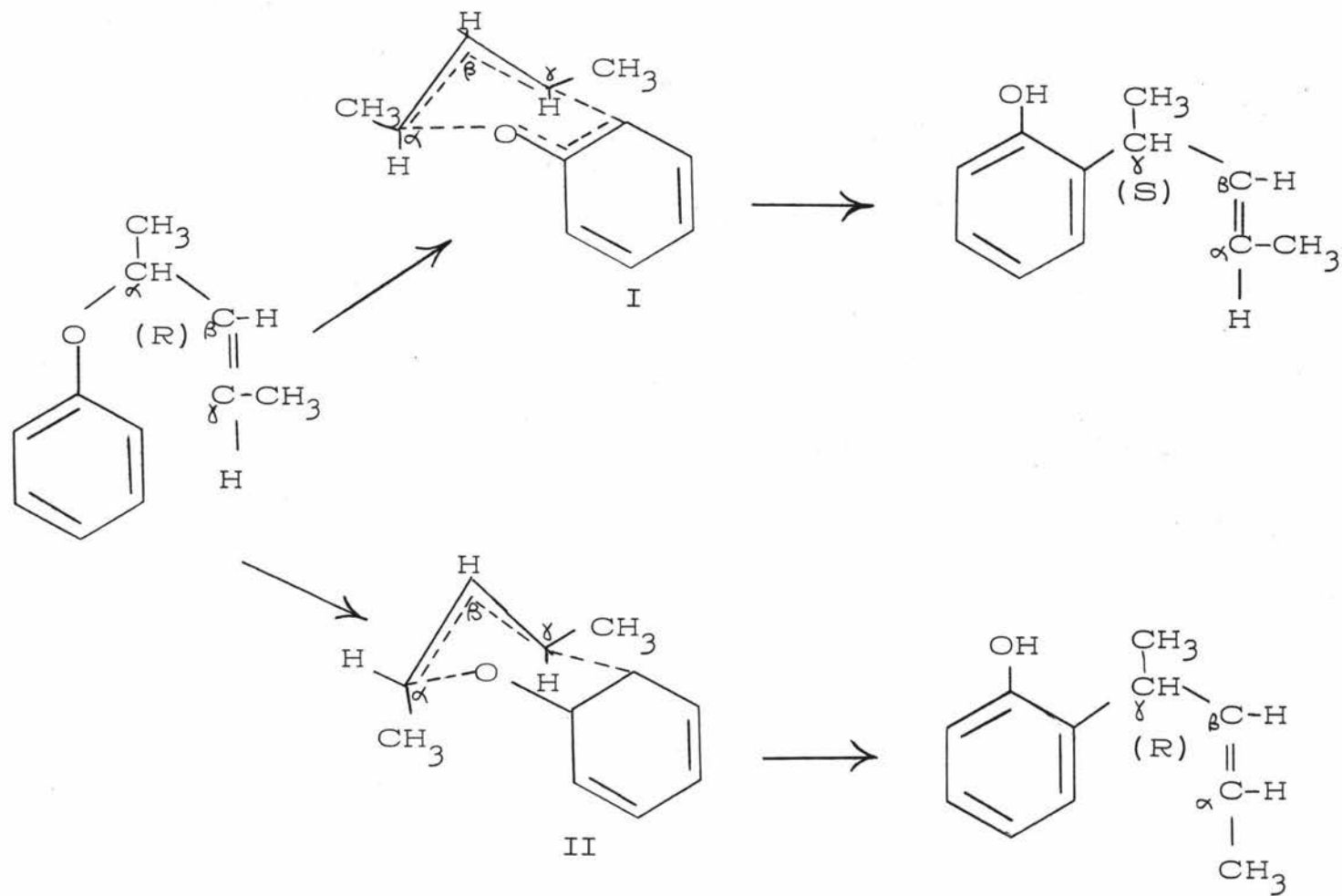


Figure 1

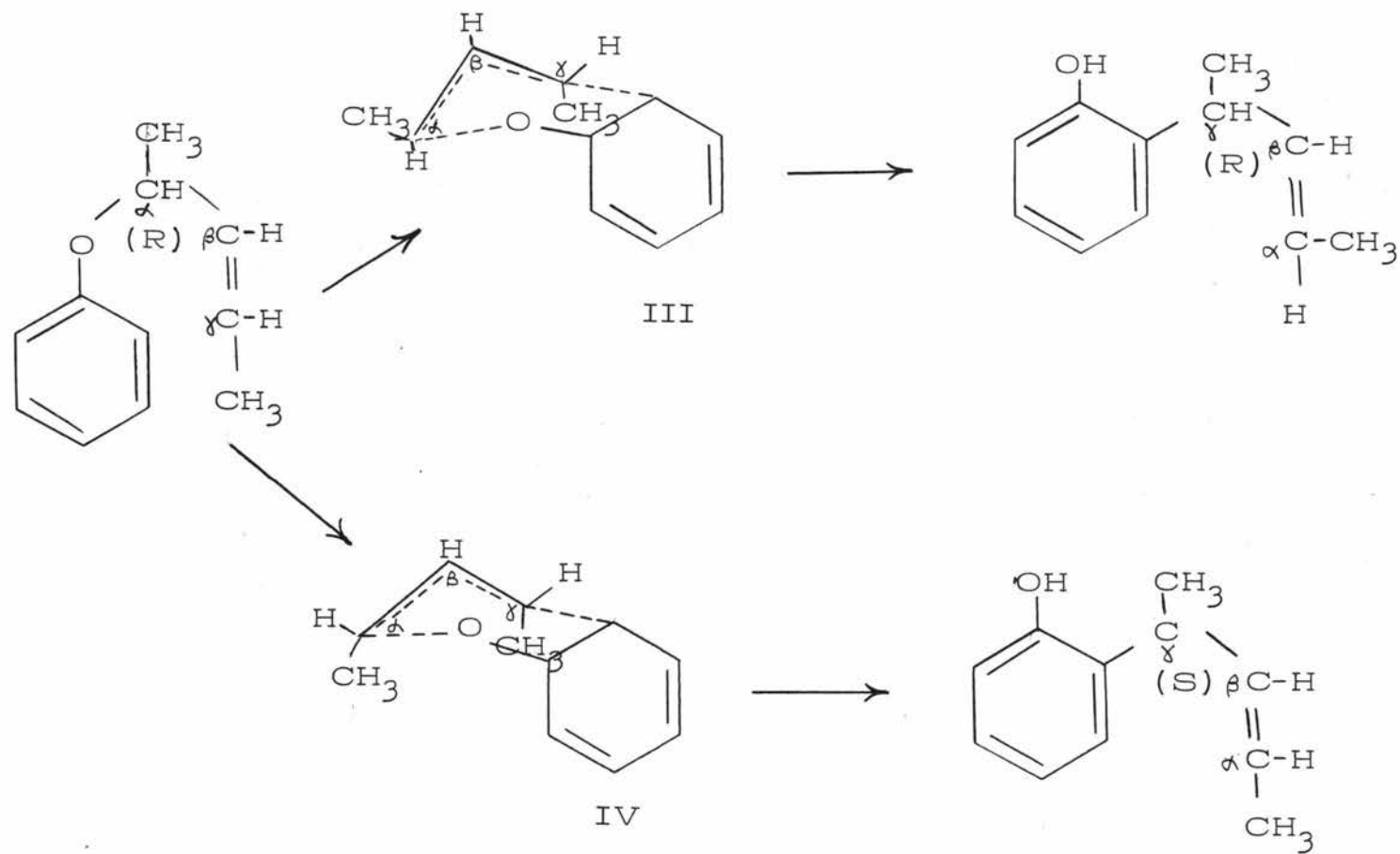


Figure 2

states. Thus, it is predicted that the rearrangement will proceed via (I) more rapidly and that the major product component will be that having an inverted configuration and a trans double bond.

In a similar manner, the models can be applied to the cis-ether. Here again, two routes are possible, via (III) or (IV). If the rearrangement proceeds through (III), the  $\chi$ -methyl group is forced into the less favorable axial-like position demanded by the initial cis double bond but the  $\alpha$ -methyl occupies an equatorial position. Here, the product retains its configuration at the asymmetric center but the new double bond is trans. Conversely, rearrangement via (IV) leaves the  $\chi$ -methyl in the axial-like position but the  $\alpha$ -methyl is now situated in an axial position. This route gives rise to a product having an inverted configuration and a cis double bond. Thus it can be concluded that the major product in the cis case will have a retained configuration and a trans double bond. Moreover, this model provides a distinct and unambiguous relation between the double bond configuration and the configuration at the asymmetric centers as shown on Table I.

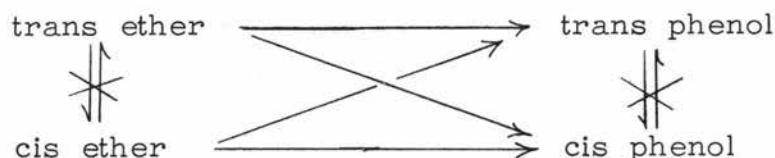
Some semi-quantitative estimates of the relative rates may also be obtained from this model. For the cyclohexane

Table I		
Double bond configuration		Asymmetric center
R-Ether	Phenol	
trans	trans	inversion
trans	cis	retention
cis	trans	retention
cis	cis	inversion

ring, the energy difference between an axial and an equatorial methyl is ca. 1.5 kcal/mole (13, p. 1367), and for the 1,3-diaxial dimethyl interaction, about 3.7 kcal/mole (1, p. 2145). If the "axial" to "equatorial" energy difference has the same value in the transition state, one can estimate about fifteen percent cis-phenol from the trans-ether on the basis of  $\Delta F_{cis}^* - \Delta F_{trans}^* = 2.3 RT \log k_{trans}/k_{cis}$ . In a similar manner, about seven percent cis-phenol would be predicted from the cis-ether. Disregarding the numerical values, the results do predict a greater cis/trans ratio from the trans-ether than from the cis-ether.

Bearing in mind that these predictions are based on a kinetic model, any data to be compared with these predictions must satisfy certain requirements. No conversion of the ether

to a configurational isomer may occur, the products must be the kinetically controlled ones and the rearrangements must be irreversible. Thus it must be known that the rearrangement takes place according to the following scheme, otherwise experimental data cannot be compared with the predictions from the model with much certainty. Only the requirement that the



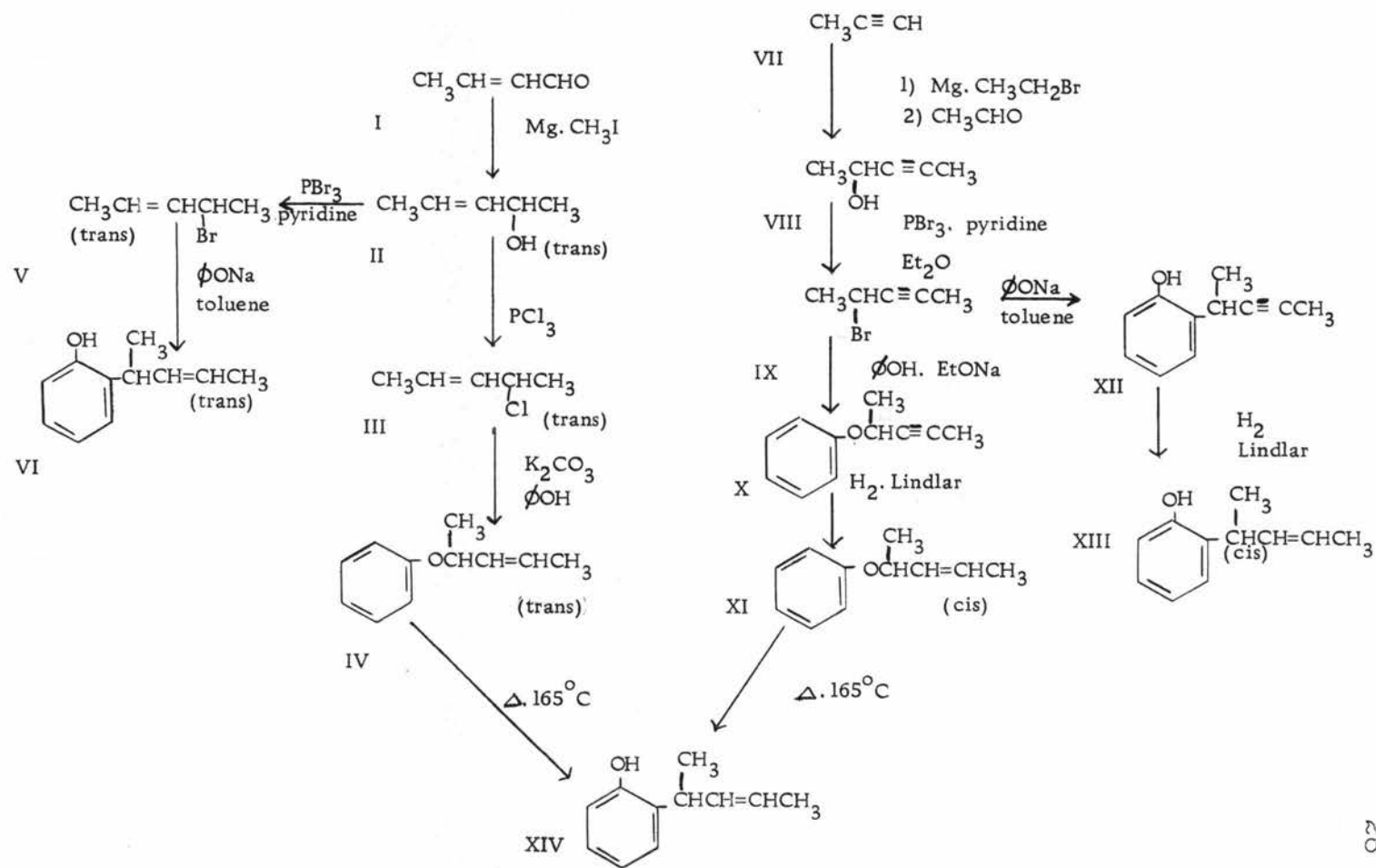
ortho-Claisen rearrangement is an irreversible process is known from previous studies.

The preliminary investigation of the Claisen rearrangement of cis and trans- $\alpha$ , $\gamma$ -dimethylallyl phenyl ethers by Marvell and Stephenson (29, p. 676) showed a general agreement with the stereochemical predictions made here. However, their results are unsatisfactory because the presence or absence of cis phenol was inferred solely on the presence or absence of a band in the infrared at  $715\text{ cm}^{-1}$  without proof that such a band is present in cis-2-(o-hydroxyphenyl)pent-3-ene. They observed conversion of the cis-ether to the trans-ether without clearly determining the relation of this conversion to product

formation. Finally, only minimal evidence was provided to show the stability of the products under the conditions of the rearrangement. Therefore, re-examination of the behavior of these ethers in a more controlled fashion will comprise the main body of this thesis.

Prior to studying the rearrangement process itself, pure cis and trans-2-(*o*-hydroxyphenyl)pent-3-ene (XIII and VI), Table II, had to be synthesized by methods independent of the rearrangement. These compounds provide the comparison standards for the products of the rearrangement. The synthetic procedure chosen had to satisfy the conditions that the side chain occupy the ortho position only, that it remain allylic and that the double bond configuration was pure cis or pure trans without contamination by the other isomer. Several attempts at preparing these isomers resulted in failure at one step or another. The best procedure found was the one patterned after the general method of heterogeneous alkylation of sodium phenoxide described by Kornblum (23, p. 2714) in which the alkylation occurs virtually exclusively at the ortho position rather than the para position. The trans-2-(*o*-hydroxyphenyl)-pent-3-ene was obtained in good yields from the reaction of dry sodium phenoxide with 2-bromopent-3-ene in toluene. The

TABLE II





presence of traces of moisture in the sodium phenoxide resulted in predominantly O-alkylated products. Infrared bands at  $3460\text{ cm}^{-1}$  (hydroxyl group),  $967\text{ cm}^{-1}$  (trans double bond), and  $750\text{ cm}^{-1}$  (mono-ortho substitution) provide strong evidence for this compound. The ultraviolet spectrum showed no conjugation of the double bond with the aromatic ring, and the nuclear magnetic resonance spectrum is in agreement with this structure. The cis isomers proved more difficult to prepare. To minimize the possibility of cis and trans isomerization, acetylenic compounds were used. Here the triple bond was reduced stereospecifically to the cis double bond in the last step using Lindlar catalyst poisoned with synthetic quinoline. The important intermediate for the cis series is the 2-bromopent-3-yne (IX). This was obtained by treatment of 2-hydroxypent-3-yne (VIII) with phosphorus tribromide as described by Smith and Swenson (38, p. 2964). It showed an infrared band at  $2230\text{ cm}^{-1}$  indicative of a disubstituted acetylene. An infrared band at  $1600\text{ cm}^{-1}$  was observed in the initially distilled material. This peak was reported as an anomalous one for some propargyl alcohols and bromides by Wotiz et al. (43, p. 5055). However, infrared analysis of a sample carefully purified by gas phase chromatography showed no band in this

region. The peak may be attributed to an impurity but it is not of the P-O-C type which is characterized by a band at  $1050-990\text{ cm}^{-1}$  (3, p. 331). The identity of the impurity was not pursued.

Heterogeneous alkylation of sodium phenoxide with 2-bromopent-3-yne proceeded smoothly to give good yields of the 2-(o-hydroxyphenyl)pent-3-yne (XII). Although no band at  $2250\text{ cm}^{-1}$  for a triple bond was observed, elemental analysis, subsequent reduction over Lindlar catalyst to the corresponding cis-phenol (XIII), and the infrared bands at  $3460\text{ cm}^{-1}$  (hydroxyl group),  $790\text{ cm}^{-1}$  (mono-ortho substitution) are in agreement with this structure.

The cis-2-(o-hydroxyphenyl)pent-3-ene (XIII) was obtained via hydrogenation of (XII) over Lindlar catalyst poisoned with synthetic quinoline. The hydroxyl band at  $3460\text{ cm}^{-1}$ , mono-ortho substitution band at  $750\text{ cm}^{-1}$  and the cis double bond at  $705\text{ cm}^{-1}$  support this structure. Furthermore, ultraviolet and nuclear magnetic resonance spectroscopy are appropriate for such a structural assignment.

The trans-ether (IV) is known and was synthesized according to the method described by Alexander and Kluiber (2, p. 4305). This ether was characterized by the presence

of a trans double bond at  $960\text{ cm}^{-1}$  and the ether band at  $1235\text{ cm}^{-1}$ . No band at  $715\text{--}705\text{ cm}^{-1}$  was observed.

The 2-phenoxy-pent-3-yne (XI) used in the preparation of the cis-ether had been prepared previously from 3-phenoxy-but-1-yne, methyl iodide and lithium in liquid ammonia (29, p. 676). The synthetic method used here consisted of allowing 2-bromopent-3-yne to react with phenol in the presence of sodium ethoxide. The product obtained was characterized by the infrared bands at  $2260\text{ cm}^{-1}$  (disubstituted triple bond),  $1603$  and  $1506\text{ cm}^{-1}$  (aromatic ring), and  $1235\text{ cm}^{-1}$  (ether linkage), indicative of an aryl propargyl ether. Reduction of this compound to the cis-ether (XI) over Lindlar catalyst was erratic. At times the hydrogen uptake was rapid and quantitative but occasionally no hydrogen absorption occurred. It was found that in general, pre-hydrogenating the catalyst and distilling the acetylenic compound immediately prior to hydrogenation improved the reduction. The cis-2-phenoxy-pent-3-ene obtained by this hydrogenation was characterized by the infrared bands at  $1603$ ,  $1496$ ,  $1475\text{ cm}^{-1}$  (aromatic ring),  $1240\text{ cm}^{-1}$  (ether linkage), and  $718\text{ cm}^{-1}$  (cis double bond), and absence of a band at  $970\text{ cm}^{-1}$  indicative of the trans double bond.

All rearrangements were carried out in normal octane

solution. Varying concentrations of the cis- and trans-ethers, (XI) and (IV), were placed in small pyrex bombs and sealed under vacuum. At given time intervals, samples were removed and the solvent evaporated under vacuum. It was shown from a solution containing known concentrations of the phenol product, normal octane and carbon disulfide, that there was no overlapping of the hydroxyl band at  $3460\text{ cm}^{-1}$  and the carbon-hydrogen stretching band at  $3000\text{ cm}^{-1}$ . Therefore, the technique of concentrating the samples to an arbitrary weight and making weighed analytical samples from the concentrates and carbon disulfide allowed the determination of percent phenol from the standard curve. Furthermore, the solvent had little influence on the standard curve as shown by Figure 3. This plot consists of known concentrations made up in toluene, normal octane, carbon disulfide and combinations thereof.

The concentration of the phenolic product in the samples played an important role in its analysis by the infrared band at  $3460\text{ cm}^{-1}$ . The more dilute solutions showed a splitting of the hydroxyl band into two peaks, one due to free hydroxyl and the other due to hydrogen-bonded hydroxyl groups. Using the standard dilution procedure to decrease the hydrogen bonding was not successful. The free hydroxyl peak did not

show an increase in intensity nor did the hydrogen-bonded hydroxyl band decrease on dilution. Consequently, it was necessary to prepare the analytical samples so that the phenol concentration lay in the range of 10-15% where no band splitting occurred.

After analyzing the concentrates for total phenol, they were diluted with petroleum ether and the phenolic products (XIV) isolated by alkaline extraction. To insure complete separation of the phenolic material, extraction with sodium hydroxide was followed by Claisen's alkali. No cis to trans isomerization occurred on extraction with Claisen's alkali (18, p. 1967). Samples of the phenolic products were distilled and solutions in carbon disulfide were analyzed for cis- and trans-phenol at  $715\text{-}705\text{ cm}^{-1}$  and  $970\text{ cm}^{-1}$  respectively. Quantitative measurement of the cis-phenol at  $715\text{-}705\text{ cm}^{-1}$  did not prove possible because of the low intensity of that band and interference with nearby bands. However, by comparison of a typical sample of products from the cis-ether with one from the trans-ether, Figure 9, the cis-phenol appears in both but there is less in the one from the cis-ether. Again, this can be shown by measuring the amount of trans-phenol from the  $970\text{ cm}^{-1}$  band, Table III. With the limited data available,

the trans-ether produces 85-90% trans-phenol whereas the cis-ether gives rise to 97-100% of the trans-phenol.

Having established the purity of the starting ethers and identity of the products it was necessary to consider the possibility of cis to trans interconversion of the ethers. In the preliminary investigation by Marvell and Stephenson (29, p. 676) this isomerization was observed. In addition, the same type of interconversion was reported by Huestis and Andrews (18, p. 1963) for the cis-X-methylallyl 2,6-dimethyl-phenyl ether. To study this phenomenon in greater detail, the ether recovered during the rearrangement of the cis-ether was studied in the infrared region of the trans double bond band,  $970\text{ cm}^{-1}$ . In addition, to check the possibility that this isomerization was due to acid catalysis by the phenolic products, the cis-ether was rearranged in the presence of added excess trans-2-(o-hydroxyphenyl)pent-3-ene (two moles of phenol to one mole of ether). In both series, no band appeared at  $970\text{ cm}^{-1}$  for the trans double bond.

The possibility of cis to trans isomerization of the phenolic product was tested by separately heating 0.3 M solutions of synthesized cis and trans-phenol in normal octane at  $165 \pm 2^\circ\text{C}$  for seventy-two hours. After removal of the

solvent and distillation, the phenols were subjected to infrared analysis. A small band at  $970\text{ cm}^{-1}$  appeared in the cis sample, which indicates the presence of 14% trans isomer. However, no cis double bond band appeared at  $715\text{--}705\text{ cm}^{-1}$  in the trans sample. Assuming that the conversion from the cis to the trans-phenol followed first-order kinetics, the rate of isomerization is slower than the rate of rearrangement by a factor of at least ten. Thus, it is reasonable to conclude that the products isolated from the rearrangement process are those due to kinetic control and not thermodynamic control.

It was of interest to determine the rates of rearrangement of the cis and trans ethers since they have not yet been reported. An attempt was made to study the kinetics of rearrangement of the trans isomer by Goering and Jacobson (14, p. 3277), but they reported that erratic results were obtained. From the total phenol concentration measured for each sample, average overall rate constants were calculated, Table III. The values obtained for the rearrangement at  $165 \pm 2^\circ\text{C}$  are as follows:  $k_{\text{trans}}^{0.3\text{M}} = 1.3 \times 10^{-5}\text{ sec}^{-1}$ ;  $k_{\text{trans}}^{0.6\text{M}} = 1.4 \times 10^{-5}\text{ sec}^{-1}$ ;  $k_{\text{cis}}^{0.3\text{M}} = 0.7 \times 10^{-5}\text{ sec}^{-1}$ ; and  $k_{\text{cis}}^{0.1\text{M}} = 0.95 \times 10^{-5}\text{ sec}^{-1}$ . These values parallel the rates for the cis and trans isomers of  $\chi$ -substituted allyl aryl ethers studied by

Huestis and Andrews (18, p. 1963) and White and Norcross (40, p. 1968). Plots of  $\log (\text{ether})_0/(\text{ether})_t$  versus time for the various solution concentrations show reasonable first-order kinetics in the initial states of rearrangement, Figures 5, 6, and 7. Curvature in the plots is observed with the more concentrated samples and is probably due to a medium effect. This is eliminated on dilution as shown in Figure 7. It was also found from a separate rearrangement of a 1 M solution of cis and trans-ethers in mesitylene, that the cis/trans product ratio was comparable to the ratio obtained by rearrangement in normal octane.

An attempt was made to determine the individual rates of formation of the cis and trans-phenol from each ether. From the predictions made earlier, the rate of formation of the cis-phenol from the trans-ether should be greater than that from the cis-ether. Because the amount of cis-phenol formed from both isomers was too small to measure quantitatively by infrared, the rates were not established. A comparison of the infrared spectra of the phenolic products from each ether is shown in Figures 8 and 9.

In conclusion, the experimental results obtained here under reasonably controlled conditions are in good agreement



with the predictions made on the basis of the pseudo chair model for the transition state. However, the pseudo boat model is not necessarily eliminated on the basis of these data alone. Doering and Roth (11, p. 67) recently provided conclusive experimental data showing the preference for the chair model in the closely related Cope rearrangement. It is thus reasonable that this model can be chosen for the Claisen rearrangement as well.

## EXPERIMENTAL

2-Hydroxypent-3-ene

2-Hydroxypent-3-ene was prepared from 43.2 g. (1.8 moles) of magnesium turnings, 265.5 g. (1.8 moles) of methyl iodide, and 105 g. (1.5 moles) of crotonaldehyde according to the method of Organic Syntheses (17, p. 696). On distillation, 111.2 g. (86% yield) of colorless liquid was obtained, b.p. 62-64° C (60 mm.),  $n_D^{24}$  1.4250; reported b.p. 119-121° C,  $n_D^{20}$  1.4277 (17, p. 696). Infrared peaks: 3460, 1678, 1455, 1370, 1298, 1150, 1120, 1065, 965, and 912  $\text{cm}^{-1}$ .

2-Chloropent-3-ene

The chloride was prepared according to the method of Levene and Haller (27, p. 706). The colorless liquid was purified by distillation through a small Fenske column, yield 88%, b.p. 53-54°C (152 mm.). Reported: b.p. 19-25°C (20 mm.),  $n_D^{20}$  1.5337 (2, p. 4305). Infrared peaks: 1675, 1455, 1380, 1217, 1165, 1020, 960 and 890  $\text{cm}^{-1}$ .

trans-2-Phenoxypent-3-ene (trans- $\alpha$ , $\gamma$ -Dimethylallyl Phenyl Ether)

This ether was prepared according to the method of

Alexander and Kluiber (2 , p. 4305). The clear liquid obtained by distillation had a boiling point at 36-37°C (0.075 mm.),  $n_D^{24}$  1.5083, yield 33%. Reported: b.p. 72°C (0.8 mm.),  $n_D^{20}$  1.5110 (2 , p. 4305). Infrared peaks: 1678, 1600, 1507, 1455, 1375, 1235, 1175, 1045, 960, 925, 750, and 690  $\text{cm}^{-1}$ .

### 2-Bromopent-3-ene

The bromide was prepared from 23 g. (0.27 mole) of 2-hydroxypent-3-ene, 7 ml. of dry pyridine and 10 ml. of phosphorus tribromide at 0°C according to the method of Young (44, p. 2051). The clear liquid was purified by distillation through a concentric tube column, b.p. 65-66°C (130 mm.),  $n_D^{23.5}$  1.4721, 51% yield. Reported: b.p. 70.2-77.2°C (145 mm.), (30, p. 1606). Infrared peaks: 1637, 1430, 1368, 1170, 1007, 965, and 730  $\text{cm}^{-1}$ .

### trans-2-(o-Hydroxyphenyl)pent-3-ene (trans-2( $\alpha$ , $\gamma$ -Dimethylallyl) Phenol)

The preparation of the trans phenol was patterned after the general method described by Kornblum (23, p. 2714). To a suspension of 15 g. (0.136 mole) of dry sodium phenoxide in 225 ml. of anhydrous toluene was added 20.5 g. (0.136

mole) of 2-bromopent-3-ene. The mixture was stirred for three days at 65°C under an oxygen-free nitrogen atmosphere. After the mixture had been cooled, water was added to dissolve the solid and the toluene layer extracted with aqueous alkali. The cooled alkaline fraction was neutralized with cold dilute hydrochloric acid and the acidified solution extracted three times with ether. The ether solution was dried over anhydrous magnesium sulfate. After removal of the magnesium sulfate by filtration, the ether was evaporated under vacuum. Distillation of the residue gave 10.72 g. (50% yield) of the ortho-alkylated product, b.p. 49-50°C (0.025 mm.),  $n_D^{23.5}$  1.5331. Reported: b.p. 71-74°C (0.05 mm.),  $n_D^{25}$  1.5318 (3, p. 4686). Infrared peaks: 3460, 1600, 1506, 1457, 1275, 1250, 967, 825 and 750  $\text{cm}^{-1}$ . UV:  $\lambda_{\text{max}}$  280  $\text{m}\mu$  ( $\epsilon$  = 2147),  $\lambda_{\text{max}}$  274  $\text{m}\mu$  ( $\epsilon$  = 2449). A higher boiling fraction, 3.18 g. (15% yield), b.p. 102°C (0.2 mm.) was obtained but was not investigated further. The O-alkylation products were obtained by evaporation of the dried toluene layer.

### 2-Hydroxypent-3-yne

The alcohol was prepared from ethylmagnesium bromide, methylacetylene and acetaldehyde in anhydrous ether.

In a three-liter three-necked round-bottomed flask equipped with a mechanical stirrer, dropping funnel and a condenser protected by a calcium chloride drying tube, were placed 72 g. (3.0 moles) of magnesium turnings and 600 ml. of anhydrous ether. To the mixture, cooled in an ice bath, 327 g. (3.0 moles) of freshly distilled ethyl bromide in 800 ml. of anhydrous ether was added over a period of 1-1.5 hours. The mixture was then heated at reflux for 2-3 hours.

Approximately 180 ml. (3.0 moles) of methylacetylene, three 60 ml. portions, were condensed in a cold trap cooled by Dry Ice and acetone. This was allowed to warm gently and the gas bubbled into the reaction mixture which was cooled in an ice-salt bath. The condenser-drying tube was connected to a second cold trap cooled by Dry Ice-acetone to collect any unreacted methylacetylene. At the end of the addition of each 60 ml. portion, the unreacted methylacetylene was recycled by reversing the positions of the cold traps. The addition time of each mole of gas varied from 3-5 hours. The mixture was kept cold throughout the addition of methylacetylene, stirred overnight, about eight hours, then refluxed

in a warm water bath four hours to drive off the ethane formed.

To the mixture, cooled in an ice-salt bath, was slowly added 180 ml. (3.0 moles) of freshly distilled acetaldehyde. The mixture was stirred 2-3 hours then refluxed three hours, allowed to cool to room temperature and stirred overnight. The solution turned from light grey to red-brown at this point.

To the cooled mixture was added 1.5 liters of saturated ammonium chloride solution. The ether layer was separated from the aqueous layer, the aqueous layer extracted with ether. After drying the combined ether layers, the ether was removed by distillation at atmospheric pressure. Distillation of the residue under vacuum gave 164.6 g. (65% yield) of a colorless liquid. Purification was accomplished by redistilling through the concentric tube column, b.p. 61-61.5°C (29 mm.),  $n_D^{24}$  1.4445. Reported: b.p. 50-55°C (16 mm.),  $n_D^{25}$  1.4467,  $d_{20}$  0.904 (38, p. 2964). Infrared peaks: 3460, 2230, 1447, 1370, 1327, 1157, 1075, 1000, and 885  $\text{cm}^{-1}$ . Phenylurethan derivative, m.p. 76°C.

### 2-Bromopent-3-yne

The bromide was prepared from 21 g. (0.25 mole)

of 2-hydroxypent-3-yne, 8 ml. of anhydrous pyridine and 12 ml. of phosphorus tribromide in 150 ml. of anhydrous ether according to the method of Smith (38, p. 2964). Distillation through the concentric tube column gave a clear liquid, b.p.  $81^{\circ}\text{C}$  (128 mm.),  $49-49.5^{\circ}\text{C}$  (28mm.),  $n_{\text{D}}^{27.5} 1.4888$ , yield 57%. Reported: b.p.  $41-44^{\circ}\text{C}$  (20mm.)  $n_{\text{D}}^{25} 1.4903$ ,  $d_{20} 1.335$ , yield 68% (38, p. 2964). Infrared peaks: 2230, 1444, 1375, 1315, 1185, 1062, 1025, 955, and  $718\text{ cm}^{-1}$ .

#### 2-Phenoxy-pent-3-yne

To a 200 ml. three-necked round-bottomed flask, equipped with a dropping funnel, a condenser protected by a calcium chloride tube, and a mechanical stirrer, and containing 115 ml. of anhydrous ethanol was added 2.83 g. (0.123 mole) of sodium. After the sodium had completely reacted, 11.56 g. (0.123 mole) of phenol was added and the mixture stirred fifteen minutes. To this solution was added 20.6 g. (0.123 mole) of 2-bromopent-3-yne, and the mixture was stirred fifteen minutes at room temperature then overnight, nine and one-half hours, at  $65^{\circ}\text{C}$ . The solution was cooled to room temperature and stirred an additional ten hours. After the solution had been concentrated under vacuum, enough water

was added to dissolve the solids. The aqueous solution was extracted three times with 50 ml. portions of ether. The combined ether solution was extracted three times with 10% sodium hydroxide, washed once with water and dried overnight over anhydrous sodium sulfate. The ether solution was filtered, the ether removed under vacuum and the residue distilled.

On distillation under vacuum, 11.79 g. (60% yield) of colorless liquid was obtained, b.p. 48-49°C (0.10 mm.),  $n_D^{24}$  1.5220.

Reported: b.p. 59.5-60°C (0.65 mm.),  $n_D^{20}$  1.5254 (29, p. 676). Infrared peaks: 2260, 1603, 1500, 1450, 1335, 1235, 1164, 1080, 1070, 1005, 925, 755, and 690  $\text{cm}^{-1}$ . UV:  $\lambda_{\text{max}}^{275} \text{ m}\mu$  ( $\epsilon$  = 1527),  $\lambda_{\text{max}}^{271} \text{ m}\mu$  ( $\epsilon$  = 1794),  $\lambda_{\text{max}}^{263} \text{ m}\mu$  ( $\epsilon$  = 1382).

cis-2-Phenoxy-pent-3-ene (cis- $\alpha$ , $\gamma$ -Dimethylallyl Phenyl Ether)

This ether was prepared by hydrogenation of the corresponding acetylenic ether using 10% by weight Lindlar catalyst, quinoline and anhydrous ethyl acetate as the solvent. After the calculated amount of hydrogen had been adsorbed, the hydrogenation was stopped and the catalyst removed by filtration. The ethyl acetate was removed under vacuum and



the residue distilled. The product distilled at 31-32°C (0.030 mm.),  $n_D^{24}$  1.5068. Reported: b.p. 45°C (0.6 mm.),  $n_D^{20}$  1.5102 (29, p. 676). Infrared peaks: 1603, 1496, 1475, 1350, 1240, 1170, 1080, 1025, 955, 930, 753, 718, and 690  $\text{cm}^{-1}$ .

2-(o-Hydroxyphenyl)pent-3-yne

The phenol was prepared by the general method described by Kornblum (23, p. 2714). A mixture of 11.6 g. (0.1 mole) of anhydrous sodium phenoxide and 14.8 g. (0.1 mole) of 2-bromopent-3-yne in 150 ml. of anhydrous toluene was stirred three days at 65°C under a nitrogen atmosphere. The mixture was cooled to room temperature and the phenolic products isolated in the manner described for trans-2-(o-hydroxyphenyl) pent-3-ene. A colorless liquid, 7.45 g. (46% yield), was obtained which distilled at 78-80°C (0.275 mm.),  $n_D^{23.5}$  1.5430. Infrared peaks: 3475, 1595, 1485, 1450, 1340, 1325, 1270, 1215, 1085, 1036, 835, and 790  $\text{cm}^{-1}$ .

Anal: Calc. for  $\text{C}_{11}\text{H}_{12}\text{O}$ : C, 82.47%; H, 7.55%.

Found: C, 82.39%; H, 7.71%.

Phenylurethan derivative: m.p. 87°C.

Anal: Calc. for  $\text{C}_{18}\text{H}_{17}\text{O}_2\text{N}$ : C, 77.39%; H, 6.12%

Found: C, 77.0%; H, 6.60%.

The O-alkylated product, 2.29 g. (14% yield), obtained had an infrared spectrum identical with the 2-phenoxy-pent-3-yne prepared above.

cis-2-(o-Hydroxyphenyl)pent-3-ene (cis-2-( $\alpha$ ,  $\gamma$ -Dimethylallyl) phenol)

This phenol was obtained by catalytic hydrogenation of 2-(o-hydroxyphenyl)pent-3-yne at atmospheric pressure. Ten to fifteen percent by weight of Lindlar catalyst in 25-30 ml. of anhydrous ethyl acetate containing two drops of synthetic quino-line were used. The hydrogenation was stopped after the adsorption of the calculated amount of hydrogen and the product isolated in the usual manner. In general, the induction period was shortened by distilling the starting material immediately prior to hydrogenation. A clear liquid was obtained by distillation, b.p. 63-65°C (0.25 mm.),  $n_{D}^{23.5}$  1.5347. Infrared peaks: 3460, 1600, 1506, 1457, 1405, 1275, 1250, 930, 825, 750, and 705  $\text{cm}^{-1}$ . UV:  $\lambda_{\text{max}}$  280  $\text{m}\mu$  ( $\epsilon$  = 2387),  $\lambda_{\text{max}}$  274  $\text{m}\mu$  ( $\epsilon$  = 2744).

Anal: Calc. for  $\text{C}_{11}\text{H}_{14}\text{O}$ ; C, 81.44%; H, 8.69%

Found: C, ; H,

### NMR Spectra of *cis* and *trans*-2-(*o*-Hydroxyphenyl)pent-3-ene

NMR spectra of the synthesized *cis* and *trans*-2-(*o*-hydroxyphenyl)-pent-3-ene were made on the Varian A-60 High Resolution NMR Spectrophotometer.

*trans*-2-(*o*-Hydroxyphenyl)pent-3-ene, (50%  $\text{CCl}_4$  solution, 2 drops tetramethyl silane):  $\text{CH}_3\text{CH}-$ , doublet,  $\tau = 8.75$ ,  $J = 7$  cps;  $\text{CH}_3\text{CH}=$ , doublet,  $\tau = 8.43$ ,  $J = 4$  cps;  $\text{OCH}-$ , multiplet centered at  $\tau = 6.33$ ; *trans*- $\text{CH}=\text{CH}-$ , multiplet centered at  $\tau = 4.50$ ;  $\text{OH}$ , singlet,  $\tau = 4.12$ ; and aromatic  $\text{H}$ , multiplet centered at  $\tau = 3.15$ .

*cis*-2-(*o*-Hydroxyphenyl)pent-3-ene, (neat):  $\text{CH}_3\text{CH}-$ , doublet,  $\tau = 8.83$ ,  $J = 7$  cps;  $\text{CH}_3\text{CH}=$ , doublet,  $\tau = 8.53$ ,  $J = 5$  cps;  $\text{OCH}-$ , multiplet centered at  $\tau = 6.03$ ; *cis*- $\text{CH}=\text{CH}-$ , multiplet centered at  $\tau = 4.60$ ; and aromatic  $\text{H}$ , multiplet centered at  $\tau = 3.20$ .

### Attempted preparation of pent-2-yne-3-yl-p-toluenesulfonate

Three attempts were made to prepare the ester.

a. According to the directions of Reppe (32, p. 78), to 6.4 g. of 35% sodium hydroxide were added 4.2 g. (0.05 mole) of 2-hydroxypent-3-yne and 10.48 g. (0.055 mole) of

p-toluenesulfonyl chloride in 2.8 g. of water. The mixture was stirred 6.5 hours at room temperature. After being cooled in an ice bath, the solid was filtered and washed with water. The solid was shown to be p-toluenesulfonyl chloride.

b. A mixture of 1.05 g. (0.125 mole) of 2-hydroxypent-3-yne and 1.28 g. (0.016 mole) of pyridine was added to 2.93 g. (0.015 mole) of p-toluenesulfonyl chloride as described by Eglinton (12, p. 3653). The stirred mixture was kept at 20°C two days. After warming to room temperature, water was added and the mixture extracted with ether. The combined ether extracts were washed twice with ten ml. portions of 5% sulfuric acid, once with 10% sodium bicarbonate, and once with water, then dried over anhydrous magnesium sulfate. White needles of p-toluenesulfonyl chloride were obtained on evaporation of the ether.

c. To 0.90 g. (0.011 mole) of 2-hydroxypent-3-yne and 1.91 g. (0.01 mole) of p-toluenesulfonyl chloride in 20 ml. of anhydrous ether was slowly added 1.68 g. (0.025 mole) of pulverized KOH. The mixture was cooled and stirred 6.5 hours in an ice-salt bath maintained at -5 to 0°C, then stirred at room temperature 3.5 hours. The ether was decanted and enough water added to dissolve the solid. The aqueous portion

was extracted once with ether. The combined ether layers were dried over anhydrous magnesium sulfate. A black oily lachrymator resulted on removal of the ether, no crystalline tosylate was isolated.

Rearrangement of *cis*- and *trans*-2-phenoxy-pent-3-ene in  
*n*-octane

*cis*-2-Phenoxy-pent-3-ene. A 0.3 M solution (7.5022 g. in 150 ml. of solution) of *cis*-2-phenoxy-pent-3-ene in normal octane was divided into ten aliquots of 15 ml. each and placed in small pyrex bombs. The bombs were sealed under vacuum and totally submerged in a thermostatically controlled silicone oil bath at  $164 \pm 2^\circ\text{C}$ .

A 0.1 M solution (0.8086 g. in 50 ml. of solution) was divided into five aliquots of ten ml. each and placed in small pyrex bombs and sealed. The bombs were placed in a silicone oil bath maintained at  $165 \pm 1^\circ\text{C}$ . Samples were removed at given time intervals and worked up in the manner described below.

*trans*-2-Phenoxy-pent-3-ene. Two series of samples were prepared and sealed under vacuum into small pyrex bombs.

The first series consisted of ten ml. samples of 0.6 M solutions in n-octane and rearranged at  $163 \pm 2^\circ\text{C}$ . The second set was made up from a 0.3 M solution of trans ether in n-octane, (contains 7.2263 g. in 150 ml. of solution) which was divided into ten aliquots of 15 ml. each. Rearrangement was accomplished by heating at  $164 \pm 2^\circ\text{C}$  in the silicone oil bath.

Isolation of rearrangement product. Samples removed at given time intervals were cooled to room temperature and concentrated under vacuum in weighed flasks. The weighed concentrates were analyzed for total phenol by infrared.

Pertinent data for the 0.6 M and 0.3 M trans, and 0.3 M and 0.1 M cis are given on Table III. The rate constants were calculated from the equation,  $k = \frac{2.303}{\text{time (sec)}} \log \frac{(\text{ether})_0}{(\text{ether})_t}$ . Plots of  $\log \frac{(\text{ether})_0}{(\text{ether})_t}$  versus time are shown in Figures 5, 6, and 7.

After the determination of the total phenol, the concentrated solutions were diluted with five ml. of petroleum ether, then extracted three times with five ml. portions of 20% sodium hydroxide, and twice with five ml. portions of Claisen's alkali. The petroleum ether layer was washed once with water and dried over anhydrous magnesium sulfate. Evaporation of the petroleum ether under vacuum left a residue of the non-

rearranged ether which was analyzed by infrared for cis-trans interconversion. No peaks at  $970\text{ cm}^{-1}$  for the trans double bond were observed.

The alkali soluble extracts were cooled in an ice bath and neutralized with cold dilute hydrochloric acid. The acidified solutions were extracted five times with five ml. portions of ether and once with five ml. of petroleum ether. The combined ether extracts were dried over anhydrous magnesium sulfate, filtered, and the ether removed under vacuum. The concentrated residue was distilled, weighed, and analyzed by infrared for cis phenol at  $715\text{ cm}^{-1}$  and trans phenol at  $970\text{ cm}^{-1}$ , Table III. Comparison of the phenolic products from sample cis and trans ethers with that of pure cis and trans-2-(o-hydroxyphenyl)pent-3-ene in the infrared region of  $750\text{--}690\text{ cm}^{-1}$  is shown in Figures 8 and 9.

Rearrangement of cis- and trans-2-phenoxy-pent-3-ene in mesitylene

Ten ml. of a 1 M solution of cis-2-phenoxy-pent-3-ene and ten ml. of a 1 M solution of the trans ether in mesitylene were placed separately in small pyrex bombs and sealed under vacuum. The bombs were heated in a silicone oil bath

maintained at  $165 \pm 1^\circ\text{C}$  for 72 hours. The bombs were cooled and the phenolic contents isolated in the usual manner, distilled and analyzed by infrared.

Rearrangement of *cis*-2-phenoxy-pent-3-ene in the presence of added *trans*-2-(*o*-hydroxyphenyl)pent-3-ene

A solution (75 ml.) of *n*-octane containing 1.2555 g. (0.0077 mole) of *cis*-2-phenoxy-pent-3-ene, and 2.5055 g. of *trans*-2-(*o*-hydroxyphenyl)pent-3-ene, was divided into five 15 ml. aliquots which were sealed into bombs under vacuum. The samples were placed into a constant temperature bath at  $165 \pm 1^\circ\text{C}$  and removed at given time intervals. The bombs were opened, the contents concentrated and worked up in the same manner as described above for the rearrangement products. The recovered ether was analyzed by infrared for *cis-trans* interconversion. The *trans* double bond peak at  $970\text{ cm}^{-1}$  was not observed.

Equilibration of *cis*- and *trans*-2-(*o*-hydroxyphenyl)pent-3-ene

A ten ml. solution of 0.5068 g. of *cis*-2-(*o*-hydroxyphenyl)pent-3-ene in *n*-octane (0.3 M) was heated 72 hours at  $164 \pm 2^\circ\text{C}$  in a sealed bomb. The sample was cooled, the



contents concentrated and analyzed by infrared in the usual manner. A small peak at  $970\text{ cm}^{-1}$  for the trans double bond was observed, calculated 14.4%.

Likewise, a ten ml. solution of 0.5009 g. of trans-2-(o-hydroxyphenyl)pent-3-ene in n-octane (0.3 M) was heated 72 hours at  $164 \pm 2^\circ\text{C}$  in a sealed bomb, and analyzed. No indication of cis double bond was observed by infrared at  $715\text{ cm}^{-1}$ .

#### Infrared Analyses

All infrared analyses were made with a Perkin-Elmer Model 21 infrared spectrophotometer equipped with a sodium chloride prism. A fixed sodium chloride cell of 0.05 mm. path length was used for quantitative analyses. Instrument settings were: resolution 950, gain 6.5, response 1, suppression 3, and speed 3.5. The total phenol concentration was determined from the absorption at  $3460\text{ cm}^{-1}$  and the concentration of trans and cis products and/or starting materials from that at  $970$  and  $705\text{--}715\text{ cm}^{-1}$ , respectively (3, p. 34). The  $I_0$  and I values were determined by measuring the distance from the base line of no absorption to the point of zero transmission and from the peak to the zero transmission

respectively.

Samples of known concentrations of pure substance in the appropriate amounts of n-octane and  $\text{CS}_2$  were used to establish standard curves in each case, Figures 3 and 4.

At low concentrations of phenol, splitting of the hydroxyl peak at  $3460\text{ cm}^{-1}$  was observed. This splitting, probably due to hydrogen bonding, could not be eliminated by further dilution with  $\text{CS}_2$ . Therefore, all samples were prepared so that the hydroxyl concentrations lie in the range of 10-15% solution where no splitting of the peak occurred. Furthermore, the ratio of n-octane/ $\text{CS}_2$  was found to have no influence on the analysis.

## SUMMARY

In order to study the stereochemistry of the Claisen rearrangement, the cis- and trans-2-phenoxy-pent-3-enes ( $\alpha$ ,  $\gamma$ -dimethylallyl phenyl ethers) were re-examined.

A definite relationship between the double bond configuration and the configuration of the asymmetric center is shown by assuming the cyclohexane chair model for the transition state. Various predictions can be made using this model as shown on Table I. These predictions were based on the requirements that there was no interconversion of the ethers and that the products isolated were due to kinetic control. Under those conditions, certain of the predictions were experimentally confirmed. Thus, both the cis- and trans-ethers gave trans-2-(o-hydroxyphenyl)-pent-3-ene as the major product. In addition, it was shown qualitatively that the cis to trans product ratio was larger for the trans-ether than the cis-ether. This again, is in agreement with predictions made from this model.

On the basis of an infrared method of analysis, the trans-ether was shown to rearrange faster ( $k = 1.3 \times 10^{-5} \text{ sec}^{-1}$  at  $165^\circ\text{C}$ ) than the cis-ether ( $k = 0.95 \times 10^{-5} \text{ sec}^{-1}$  at  $165^\circ\text{C}$ ).

TABLE III

Rearrangement of cis- and trans-2-phenoxyent-3-eneA. cis-2-Phenoxyent-3-ene, 0.3 M (7.5022 g./150 ml. n-octane solution)

Sample No.	Time hrs.	Total g. Phenol	% Rearrange-ment	% <u>trans</u> phenol	$\log \frac{(\text{ether})_0}{(\text{ether})_t}$	$k \times 10^{-5} \text{ sec}^{-1}$
6	1	0.0127	1.69	---	0.0074	0.474
7	2	0.0271	3.61	---	0.0159	0.509
9	3	0.0480	6.39	---	0.0287	0.612
10	5	0.0831	11.07	---	0.0560	0.716
11	8	0.1400	18.66	98	0.0897	0.718
8	10	0.2366	31.53	97	0.1645	1.05
12	14	0.2421	32.27	92	0.1692	0.774
13	18	0.3829	51.04	98	0.3102	1.11
14	24	0.5631	75.06	103	0.6031	1.61
15	72	0.8155	--	---	---	---

Average  $k$  for 9-12 =  $0.77 \times 10^{-5} \text{ sec}^{-1}$

TABLE III

Rearrangement of cis- and trans-2-phenoxyent-3-eneB. trans-2-Phenoxyent-3-ene, 0.3 M (7.2263 g./150 ml. n-octane solution)

Sample No.	Time hrs.	Total g. Phenol	% Rearrange-ment	% <u>trans</u> phenol	$\log \frac{(\text{ether})_o}{(\text{ether})_t}$	$k \times 10^{-5} \text{ sec}^{-1}$
16	1	0.0306	4.23	---	0.0188	1.21
17	2	0.0533	7.37	---	0.0333	1.07
18	3	0.0780	10.79	---	0.0496	1.06
19	5	0.1574	21.78	---	0.1067	1.37
20	8	0.2301	31.84	91	0.1665	1.33
21	10	0.2758	38.17	---	0.2098	1.33
22	14	0.4905	67.88	93	0.4932	2.31
23	18	0.5833	80.72	90	0.7149	2.54
24	24	0.7312	100	88	---	---
25	72	1.1287	---	86	---	---

Average  $k$  for 16-21 =  $1.3 \times 10^{-5} \text{ sec}^{-1}$

TABLE III

Rearrangement of cis- and trans-2-phenoxy-pent-3-eneC. trans-2-Phenoxy-pent-3-ene, 0.6 M n-octane solution

Sample No.	Time hrs.	Total g. Phenol	% Rearrangement	% <u>trans</u> phenol	$\log \frac{(\text{ether})_0}{(\text{ether})_t}$	$k \times 10^{-5} \text{ sec}^{-1}$
13	7	0.3366	33.7	---	0.179	1.64
14	17	0.4463	44.5	89	0.256	0.96
15	24	0.6768	67.6	87	0.490	1.31
16	41	0.9122	91.1	86	1.054	1.64
17	72	0.9932	97.9	82	1.670	1.48
18	168	---	100	81	---	---

Average  $k = 1.4 \times 10^{-5} \text{ sec}^{-1}$

TABLE III

Rearrangement of cis- and trans-2-phenoxy-pent-3-eneD. cis-2-Phenoxy-pent-3-ene, 0.1 M (0.8086 g./50 ml. n-octane solution)

Sample No.	Time hrs.	Total g. Phenol	% Rearrangement	$\log \frac{(\text{ether})_0}{(\text{ether})_t}$	$k \times 10^{-5} \text{ sec}^{-1}$
1	3	0.0147	9.09	0.041	0.88
2	6	0.0294	18.18	0.087	0.93
3	9	0.0430	26.59	0.134	0.95
4	12	0.0578	35.43	0.190	1.01
5	15	0.0651	40.26	0.224	0.95

Average  $k = 0.95 \times 10^{-5} \text{ sec}^{-1}$

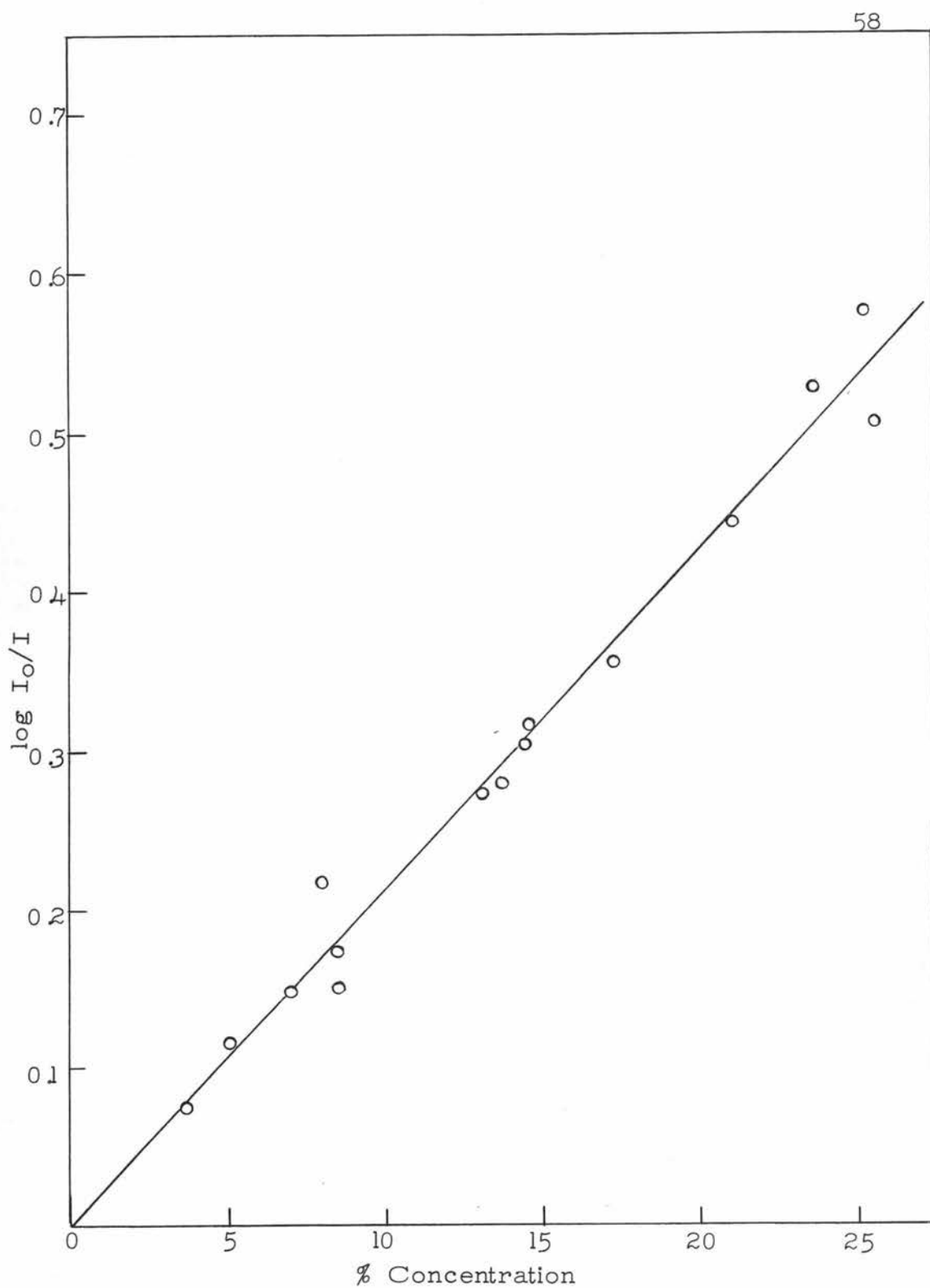


Figure 3. Standards, *trans*-2-(*o*-hydroxyphenyl)pent-3-ene,  $3460\text{ cm}^{-1}$



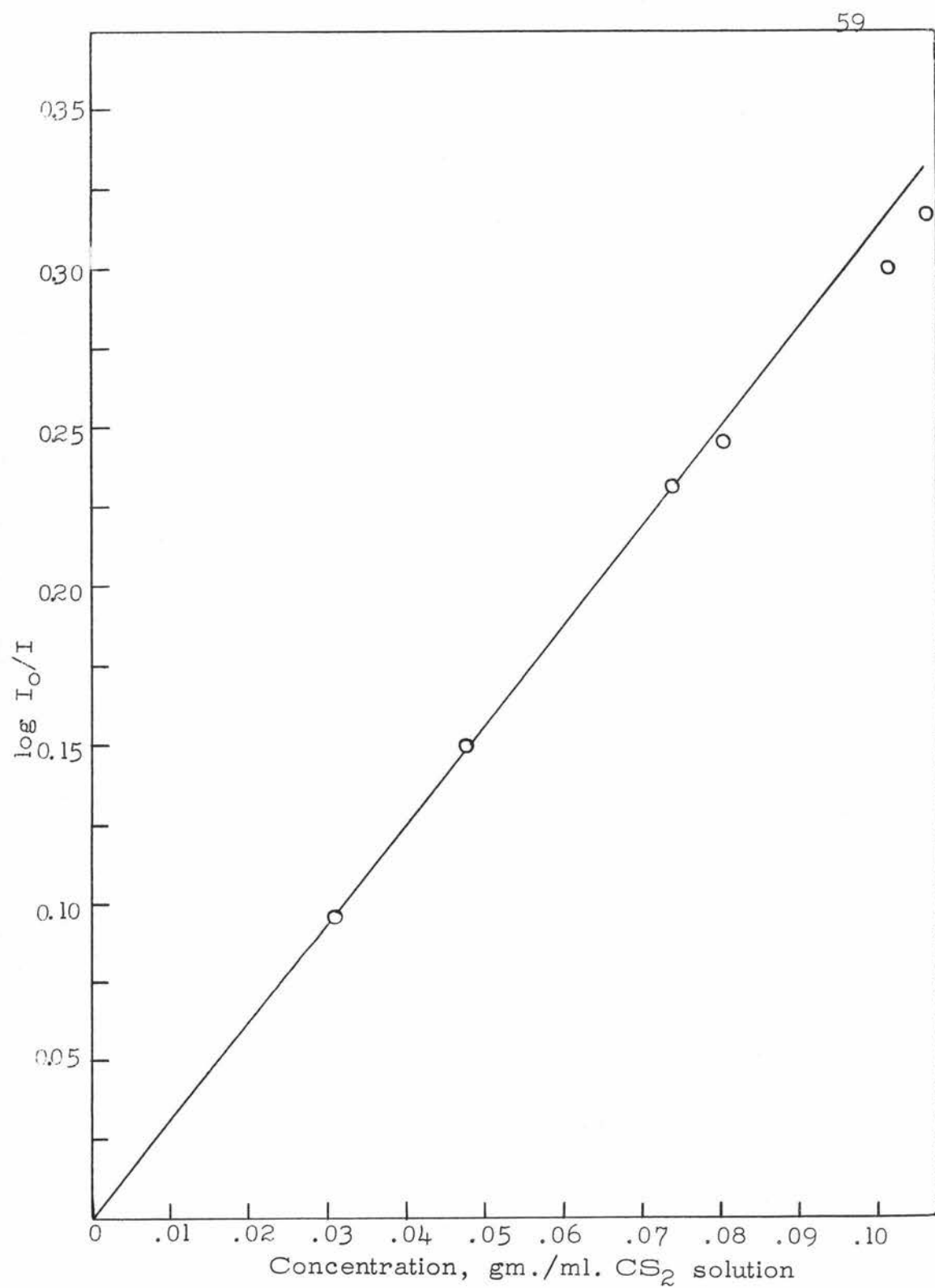


Figure 4. Standards, trans-2-(o-hydroxyphenyl)pent-3-ene  
970  $cm^{-1}$

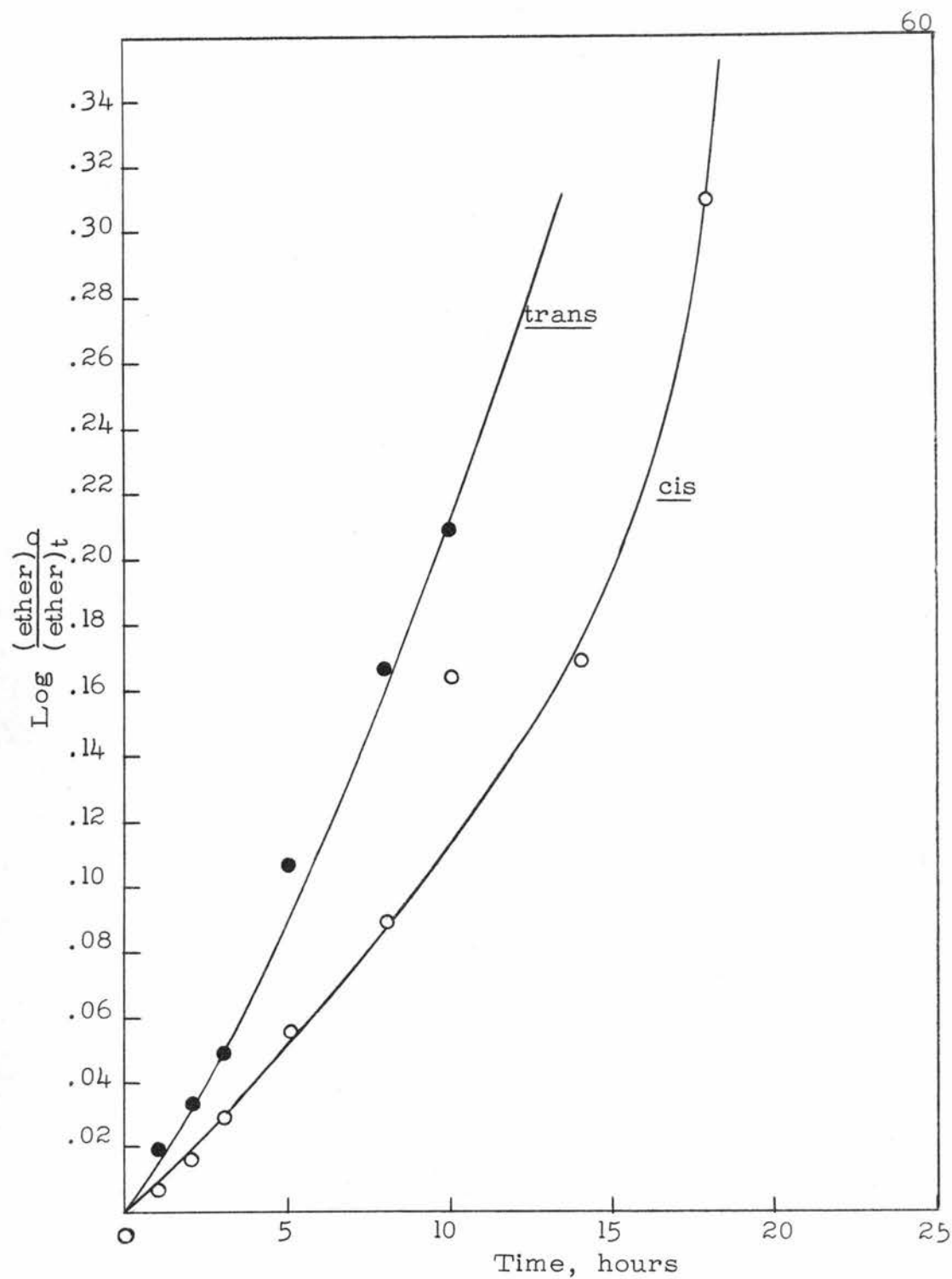
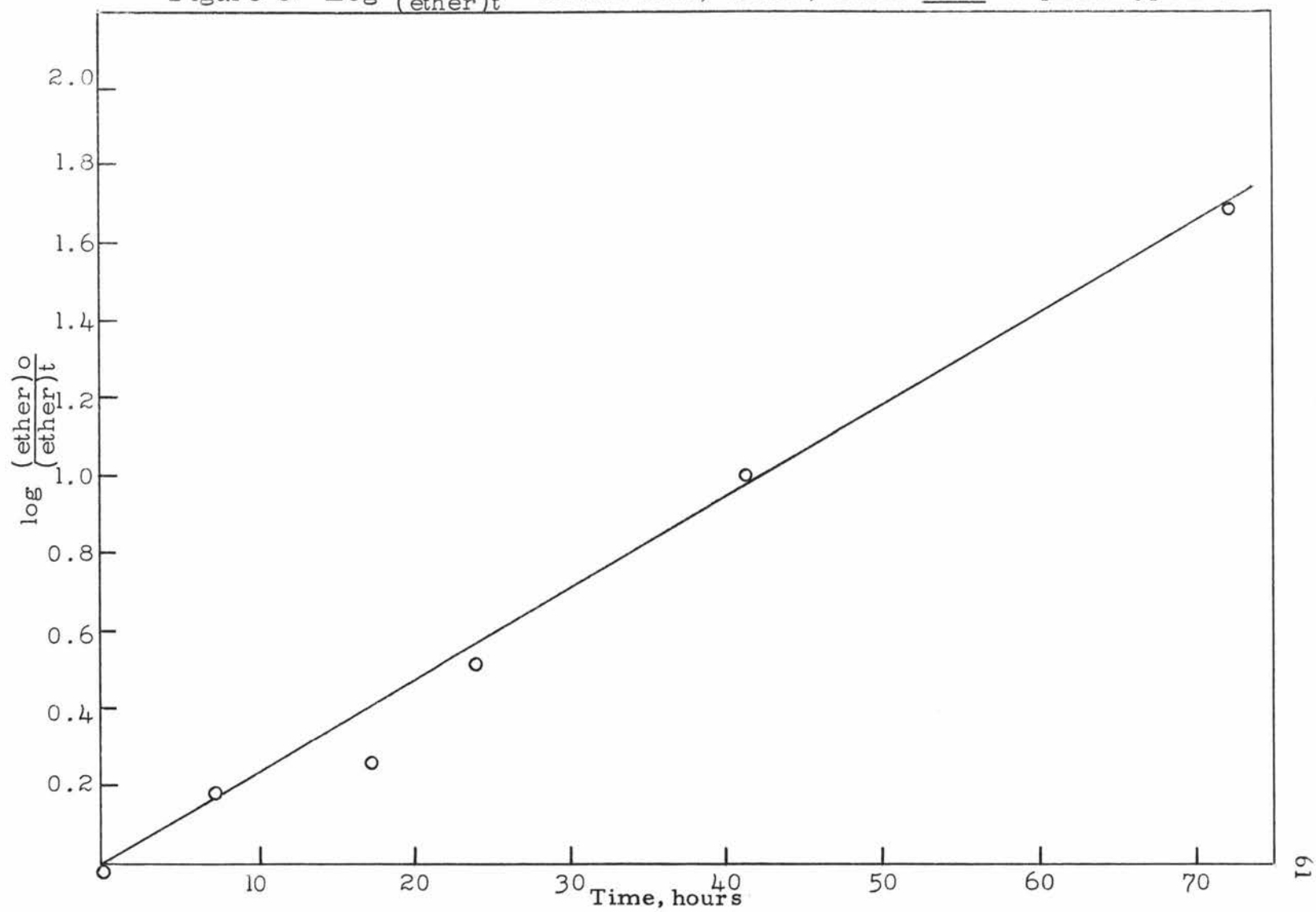


Figure 5.  $\text{Log } \frac{(\text{ether})_o}{(\text{ether})_t}$  versus time, hours; 0.3M  
cis- and trans-2-phenoxy-pent-3-ene

Figure 6.  $\text{Log } \frac{(\text{ether})_0}{(\text{ether})_t}$  versus time, hours; 0.6M trans-2-phenoxy-pent-3-ene



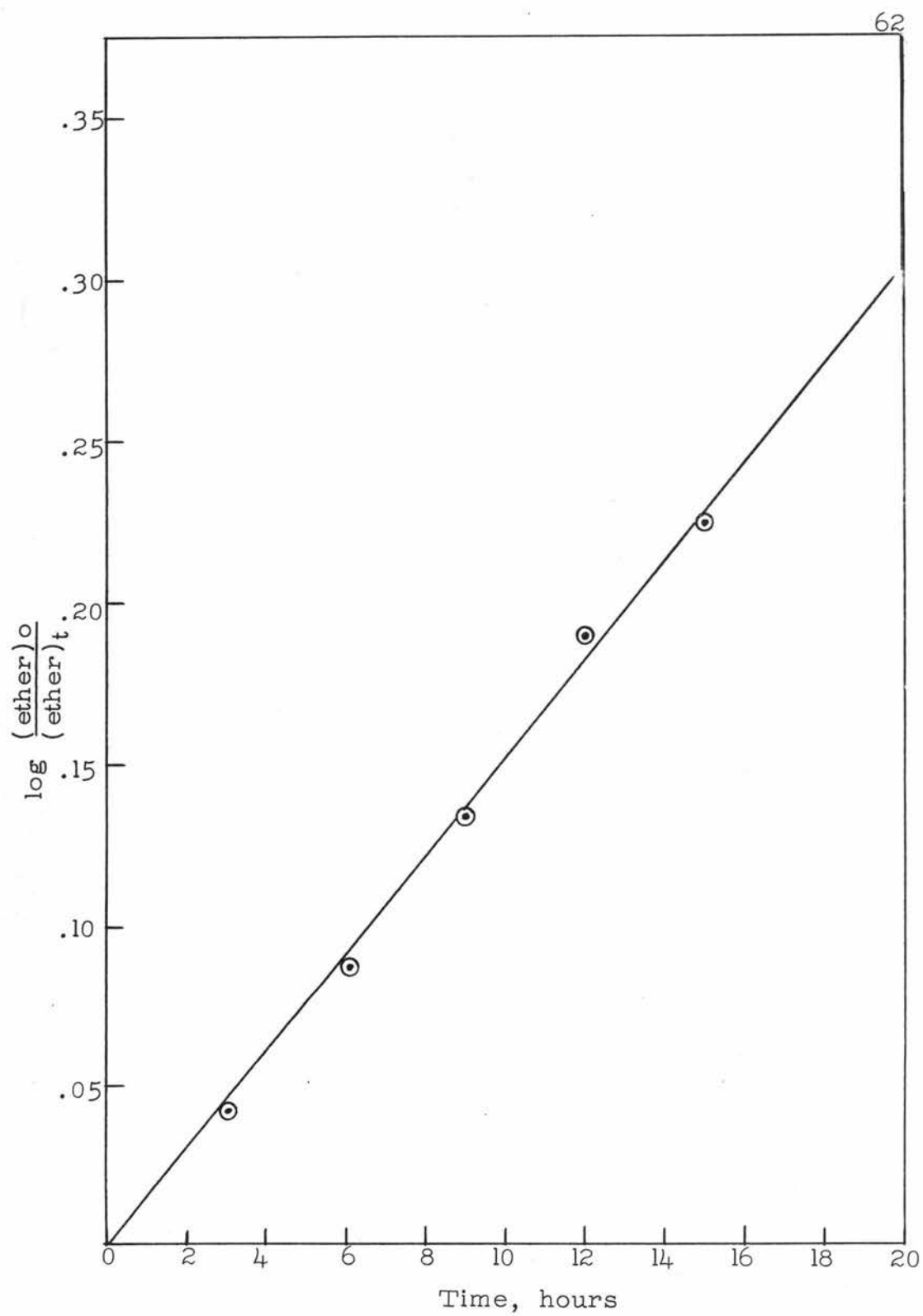


Figure 7.  $\log \frac{(\text{ether})_0}{(\text{ether})_t}$  versus time; 0.1M cis ether

Figure 8. Pure cis-and trans phenol

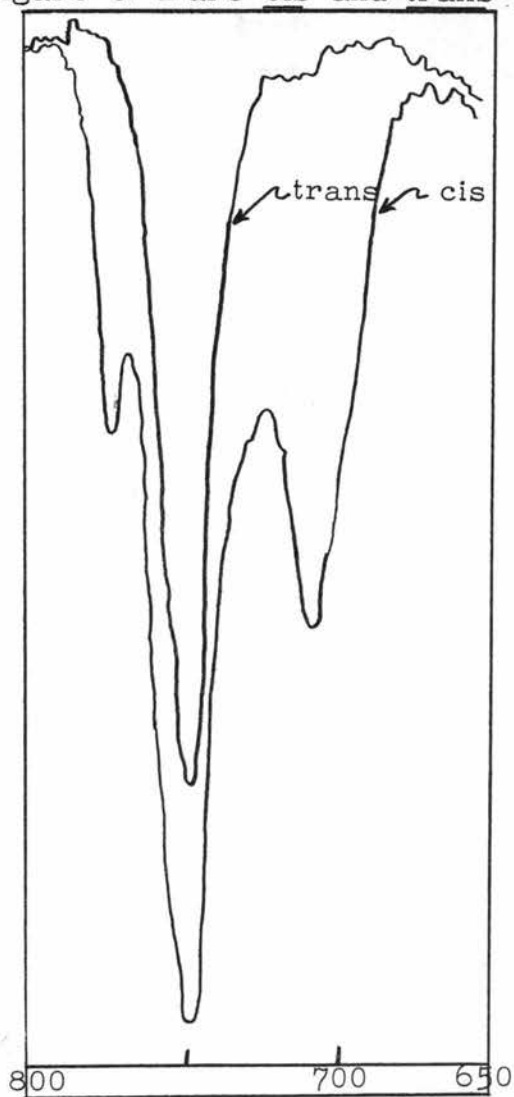
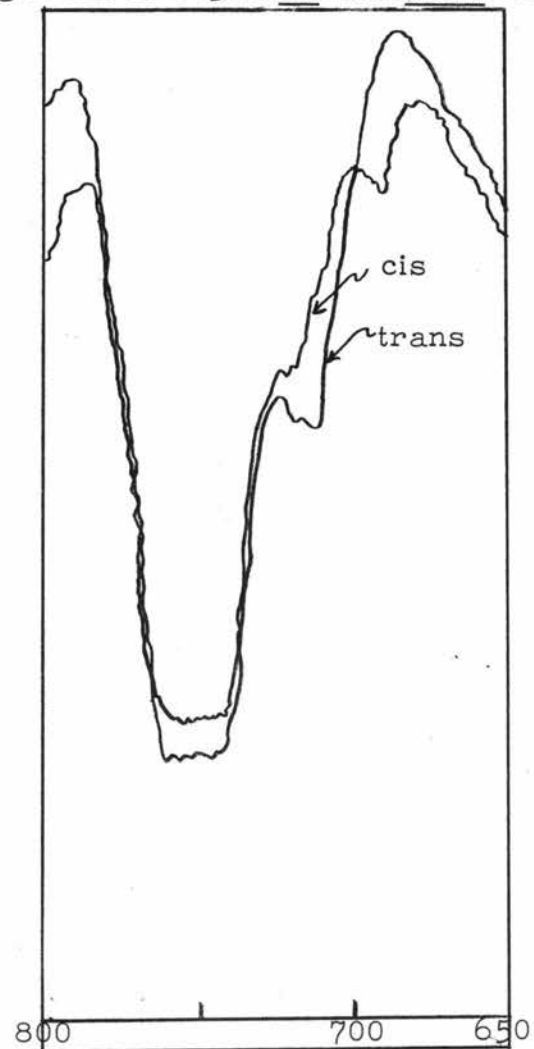


Figure 9. Phenolic Product from Re-  
arrangement of 0.3M cis and trans ether in n-octane



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